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SLOT STUDY IN RECTANGULAR TEM  
TRANSMISSION LINE

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Technical Memorandum No. 265

RESEARCH AND DEVELOPMENT  
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**HUGHES AIRCRAFT COMPANY**  
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**SLOT STUDY IN RECTANGULAR TEM**  
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**by**

**Eric Strumwasser**  
**Jo Ann Short**

**Robert J. Stegen**  
**Joseph R. Miller**

**JANUARY 1952**

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## ABSTRACT

The measured characteristics of slots in a transmission line propagating the TEM mode are given in Part I. The line consists of a rectangular outer conductor and a round inner conductor. A comparison is made between measured and theoretical results. The characteristics of dumbbell-loaded slots are shown. The results are also presented for a linear array which was designed using the dumbbell-loaded slots. In Part II the investigations were carried out in a line consisting of a rectangular outer conductor and a flat center conductor. Effects of different types of loading on resonant length and resonant frequency were investigated. The bandwidth of transverse slots as a function of shape and loading was studied and a comparison for various slot configurations is given.

## PART I

### SLOT STUDY IN RECTANGULAR TEM TRANSMISSION LINE WITH ROUND CENTER CONDUCTOR

by Robert J. Stegen and Joseph R. Miller

#### INTRODUCTION

A TEM transmission line feeding an array of slots has some advantages over a waveguide feed. The TEM line has a smaller cross-sectional area than a waveguide and, therefore, the weight and windage could be less. A TEM line branching structure feed system may be made very compact and, therefore, would probably result in a weight saving over a waveguide system. With these possible advantages in mind slots fed by a TEM transmission line were investigated.

The use of a conventional coaxial transmission line with circular inner and outer conductors as the slot feed line was undesirable for several reasons. Slotted lines of circular cross-section and of the size desired were not available, so that either a well-matched broadband transition section or a slotted line would have had to be fabricated. However, waveguide slotted lines were available which would serve as a suitable rectangular outer conductor. In addition, a rectangular outer conductor would provide a flat surface upon which to cut the slots, thereby permitting closer tolerances than on a circular outer conductor. The choice of circular rod as the center conductor was dictated by its availability. S-band was chosen as the frequency range so that slot manufacturing tolerances would be reasonable while still keeping the size of the components small.

#### DESCRIPTION OF TRANSMISSION LINE

Since the measurements were to be made at S-band, a convenient outer conductor to use was 0.4 x 0.9 inch X-band waveguide with an X-band slotted line for the impedance measurements. Standard 7/32-inch diameter aluminum rod was used for the center conductor so that the characteristic impedance ( $Z_0$ ) would be close to 50 ohms. The calculation of the  $Z_0$  of this type of transmission line is given in the Analytical

Study Section. Propagation at S-band in this transmission line was in the TEM mode. Higher modes were beyond cutoff. Figure 1 shows the impedance measuring equipment including slotted line and radiation detector. The short-circuiting plunger assembly and type N connector attachment to this TEM line are shown in Figure 2. The short-circuiting plunger is of the contacting type in which the fingers are a quarter wavelength long, making contact to the outer and inner conductors at a point of minimum current. The plunger is equipped with a screw drive and vernier scale. Poly-foam bead supports were used because of their low dielectric constant and low loss. The VSWR introduced by 1/4 inch beads was below 1.02.

A matched termination was developed which consists of a wedge of polyiron inserted in the line. This termination has the VSWR frequency characteristic as shown in Figure 3.

### ANALYTICAL STUDY

An analytical study of this type of TEM transmission line has been made by Begovich<sup>1</sup>.

The study was made using the following assumptions:

- a. The outer surface above the slot is a perfectly conducting infinite plane;
- b. The walls of the TEM line are perfectly conducting and of negligible thickness;
- c. The length of the slots is near a half free-space wavelength and is narrow in terms of wavelengths; and
- d. The line transmits only the TEM mode.

The expression for the normalized series resistance of an inclined slot placed on the center-line (of the wide-dimension side) of a TEM line having a rectangular outer conductor and a circular inner conductor is

$$R = \frac{1569}{Z_0} \frac{\ell^2}{a^2} H^2(\theta, b, a, \beta, \ell) \sin^2 \theta \quad (1)$$

where

- $\ell$  = the half-length of the slot,
- $a$  = the wide dimension of the outer conductor,
- $b$  = the narrow dimension of the outer conductor,
- $\theta$  = the angle of inclination of the slot from the longitudinal axis of the transmission line,

$Z_0$  = the characteristic impedance of the TEM transmission line, and

$$H(\theta, b, a, \beta, \ell) = \sum_{n \text{ odd}} \frac{\sinh \frac{\pi y_0}{a} \left[ \left( \frac{\pi}{2\ell} \right)^2 - (p^2 + s^2) \right] \cos(p\ell) \cos(s\ell) - 2ps \sin(p\ell) \sin(s\ell)}{\sinh \frac{\pi b}{a} \left[ \left( \frac{\pi}{2\ell} \right)^2 - (p + s)^2 \right] \left[ \left( \frac{\pi}{2\ell} \right)^2 - (p - s)^2 \right]} \quad (2)$$

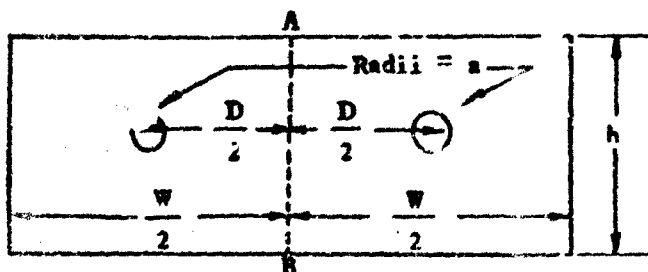
where

$$s = \beta \cos \theta$$

$$p = \frac{\pi r}{a} \sin \theta$$

and  $\left( \frac{a}{2}, y_0 \right)$  is the position of the center conductor, the x and y axes being along the wide and narrow edges of the outer conductor, respectively.

Frankel<sup>2</sup> has analyzed the balanced two-wire line shown here and has calculated the characteristic impedance to be



$$Z_0 = 276 \left\{ \log_{10} \left[ \frac{2h \tanh \frac{\pi D}{2h}}{\pi a} \right] - \sum_{m=1}^{\infty} \log_{10} \left[ \frac{1 + u_m^2}{1 - v_m^2} \right] \right\}, \quad (3)$$

where

$$u_m = \frac{\sinh \frac{\pi D}{2h}}{\cosh \frac{\pi W}{2h}},$$



and

$$\epsilon_m = \frac{\sinh \frac{\pi D}{2h}}{\sinh \frac{\pi D'}{2h}}$$

A septum may be placed along AB without upsetting the field configuration. For the usual transmission line,

$$Z_0 = \frac{1}{vC}$$

where

$v$  = the velocity of propagation in the dielectric and

$C$  = the capacity of the transmission line per unit length.

Since the capacity from one wire to the tube is twice the capacity between wires, the  $Z_0$  of a transmission line consisting of one round conductor within a rectangular tube would be one-half of that given above. For the case of the 7/32-inch rod centered within a 0.4 x 0.7-inch rectangular tube, the characteristic impedance is

$$Z_0 = 50.0 \text{ ohms.} \quad (5)$$

The capacity of a length of this transmission line was measured at 1000 cps. The  $Z_0$  calculated from this value of capacity agreed within experimental error with the theoretical value.

At 3000 mc/s with the above dimensions, (1) becomes

$$R = 38.7 \mathcal{L}^2 K^2 \sin^2 \theta. \quad (6)$$

## MEASURED RESULTS

### Unloaded Slots

Impedance data were obtained on inclined slots 0.0625 inch wide, placed on the center-line of 0.4 x 0.9 inch (inner dimension) rectangular tubing. Impedance measuring techniques similar to those used for waveguide slots<sup>3</sup> were used. A curve of resonant length as a function of angle of inclination from the center-line is plotted in Figure 4 for a frequency of 3000 mc/s. The curve is extrapolated to the zero tilt angle axis in order to provide necessary design information. An empirical expression for the resonant slot length at this frequency is

$$\ell = 1.19 + 0.003 \theta^2 \text{ inches.} \quad (7)$$

$H(\theta, b, a, \beta, \ell)$  as given by (2) can now be evaluated for the particular transmission line used. A plot of  $H^2$  at 3000 mc/s as a function of the angle of inclination of the slot from the center-line is shown in Figure 5.

A 20° resonant slot in the surface of the outer conductor has a normalized resistance at 3000 mc/s of 1.58 as compared to the value of 2.07 obtained from theory. The difference may be attributed to the finite ground plane, to the wall not being of zero thickness, and to experimental error. The measured data were obtained without a ground plane because it was felt that a two-dimensional array of these slots might be used without any ground planes.

Figures 6 and 7 are plots of normalized resistances and resonant slot lengths as functions of frequency. Figure 8 is a plot of the ratio of measured to calculated resistance as a function of slot angle. It appears that the error can be taken into account by a factor which is a linear function of the tilt angle  $\theta$ . This function is

$$K = 0.525 + 0.012 \theta \quad (8)$$

The expression for the slot resistance at 3000 mc/s now becomes

$$R = 38.7 \ell^2 H^2 K \sin^2 \theta. \quad (9)$$

Figure 9 is a plot of this empirical expression for slot resistance as a function of tilt angle,  $\theta$ , with the measured points indicated.

### Loaded Slots

Unloaded series slots which alternate about the waveguide center-line will overlap if they are spaced about a half wavelength apart. End-loading the slots will allow them to be resonant at shorter lengths and consequently keep them from overlapping. This is accomplished by making them dumbbell shaped. Figures 10 and 11 plot resonant frequency and normalized resistance as functions of dumbbell diameter for 4, 7, and 10 degree slots. These are for a constant over-all length of 2.284 inches. The curves of dumbbell diameter and normalized resistance versus tilt angle (Figure 12) were obtained from Figures 10 and 11 at 3000 mc/s.

### TEM LINEAR ARRAY

A sixteen-element linear array (Figure 13) of inclined dumbbell slots was designed for a 30 db Tchebyscheff radiation pattern. The beam position was chosen to be 10 degrees from the normal to the array at the design frequency of 3000 mc/s. This determined the element spacing. The array was terminated in a matched load. The design neglected transmission line attenuation and slot-to-slot coupling except to the dominant mode in the transmission line. The input VSWR and the radiation pattern at 3000 mc/s are shown in Figures 14 and 15. Figure 16 gives the beam position, half-power beam width and side-lobe level as a function of frequency.

The results indicate that this type of antenna is feasible. The difference between the design side-lobe level and the measured values is probably due in part to machining errors since the slots were required to be inclined at very small angles from the axis of the outer conductor. Insufficiently accurate design data may also be a contributing factor to this difference.

### ACKNOWLEDGMENTS

The authors are indebted to Dr. N. A. Begovich who proposed the rectangular TEM feed line for slot arrays and did the theoretical calculations. In addition, the authors wish to thank A. R. Margolin for his assistance with the original measurements on the straight slots.

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## PART II

### SLOT STUDY IN RECTANGULAR TEM TRANSMISSION LINE WITH FLAT CENTER CONDUCTOR

by Eric Strumwasser and Jo Ann Short

#### INTRODUCTION

The TEM strip transmission line which was built as the feed for the investigation of the slot characteristics consisted essentially of two parallel plates, spaced  $3/8$  inch apart as the outer conductor and  $3/8$ -inch by  $1/16$ -inch brass strip as the center conductor, fed through a coaxial connector and terminated in a movable short. As shown in Figure 17, the original width of the line was  $9-3/4$  inches with the feed end necked down to a width of 4 inches for attenuation of higher-order modes. Standing wave ratio and phase measurements were made with a movable probe detector inserted in a longitudinal slot cut above the center line of the center conductor. Evidence of the presence of the higher-order  $TE_{10}$  mode in the line was observed when calibration of the movable short revealed resonances occurring at positions of the short  $\lambda_g/2$  apart for this mode. Tapering the sides of the line from the 4-inch wide feed end to the  $9-3/4$ -inch width was not effective in eliminating the  $TE_{10}$  mode. The width of the line was then reduced to 4 inches throughout its length to cut off the  $TE_{10}$  mode for the L-band frequency range of 1000 to 1350 mc/s. This uniform width was interrupted for a distance of 2 inches to allow measurement of transverse resonant slots longer than 4 inches. The top plate was also cut for insertion of a 2-inch section containing the test slot. The characteristic impedance of this line was calculated to be 50 ohms. The calculations are based on equations and curves given by Begovich and Margolin<sup>1</sup>. The characteristic impedance also was experimentally determined by a measurement of the capacitance of the line. The value of 53.9 ohms obtained in this way deviates from the calculated value by less than the experimental error of the capacitance bridge used.

With a blank shorting section inserted in the 2-inch opening in the top plate, reflections in the line were measured and found to be negligible. Measurement of the relative field distribution across the line was made

by inserting a probe in a transverse slot with the movable short adjusted for minimum radiation from the slot. The results (Figure 18) show the field intensity dropping off sharply on either side of the center conductor. This distribution indicates that any higher-order modes of interest are 36 db or more below the TEM mode when there is no radiation from the slot. However, later impedance measurements made of a short dumbbell-loaded slot disclosed a discrepancy between results obtained with the line having the 2-inch wide gap left in the sides and the line having continuous sides. In these results the deviation in phase amounted to approximately  $0.03\lambda$ . No difference in VSWR was noted. The phase deviation is apparently owing to the fact that, in the presence of the radiating slot, higher-order modes exist which differ in configuration for the two different line geometries.

Significant experimental errors were introduced in the measurements by sag of the center conductor and by small changes in its lateral position produced by movement of the contacting short. A variation of  $\pm 18$  per cent in normalized resistance and  $\pm 11$  per cent in normalized reactance was found in measurements taken for various orientations of the movable short in the line. In view of this large experimental error, the results obtained with the 50-ohm line must be considered as preliminary data only. However, trends in slot characteristics as a function of various parameters have been established. Also, the knowledge gained from experimentation with this line serves as a basis for the design of a line with much improved characteristics.

## IMPEDANCE MEASUREMENTS

The slot characteristics described in the following paragraphs were measured with the 50-ohm TEM transmission line with the 2-inch gap left in the side walls. The measurement procedure for all impedance measurements is the slotted line technique described by R. J. Stegen<sup>2</sup>.

Resonant length and normalized resonant resistance of a centered straight transverse slot  $1/16$  inch wide are shown as a function of frequency in Figure 19. The resonant length remains close to one-half wavelength throughout the frequency range.

To obtain a variation of resistance for a fixed frequency, the slot was offset transversely from the center conductor. The normalized resistance and the reactance of a 5-inch long,  $1/16$ -inch wide transverse slot were measured as a function of offset for several frequencies near resonance and the results are shown in Figures 20 and 21.

Various methods of loading were investigated in order to shorten the resonant length of the slot. By terminating a slot in circular holes, a slot of 3 inches over-all length with 1-inch-diameter dumbbells was found to be resonant at very nearly 1200 mc/s, which corresponds to resonance for a 5-inch by 1/16-inch straight slot. The normalized resistance and the reactance of this dumbbell-loaded slot are plotted as a function of offset from the center conductor for a number of frequencies near resonance (Figures 22 and 23). The effects of dielectric loading were also investigated. A 3-inch long, 1/2-inch wide slot was filled with various dielectrics and the resonant frequency measured as a function of dielectric constant (Figure 24). The dielectric materials consisted of polystyrene containing various percentages of titanium dioxide. It has also been noted that, by combining dumbbell end-loading with dielectric loading in the straight portion of a slot, resonant slots as short as  $1/8\lambda$  can be obtained.

Variation of resonant resistance at a fixed frequency can also be accomplished by the use of inclined slots. The resistance of a slot is a function of the angle of inclination between the slot center line and the longitudinal axis of the center conductor. With a slight modification of the transmission line, angular slot impedance measurements can also be made.

If the resonant frequency of a slot is defined as that frequency at which the slot impedance is real, the curves in Figures 21 and 23 indicate that the resonant frequency of a transverse slot is a function of offset as well as a function of its shape and loading. If a design curve is desired for a linear array in which resonant radiators are to be used, the variation in resonant frequency with offset must be compensated for by variation of dumbbell size or by a change of dielectrics. This would require a large number of additional measurements.

Because it was felt that the variation in resonant frequency with offset might be caused by the 2-inch gap in the sides of the 50-ohm line, and as a number of other limitations of this transmission line became apparent, ideas for an improved design were developed. A line was designed and was built which used an increased spacing of 1-1/4 inch between top and bottom plates and thus made impedance measurements less sensitive to variations in the position of the center conductor. This line has the same 3/8-inch x 1/16-inch center conductor dimensions and a constant width of 3.9 inches. As a result of the increased spacing, the calculated value of the characteristic impedance was 100 ohms<sup>1</sup>. Measurement of the capacitance of this line furnished a value of characteristic impedance of 107 ohms, which deviates from the calculated value by less than the experimental error of the capacitance bridge used for the measurement. The normalized resonant

resistance of a slot in this 100-ohm line should theoretically be half of its value in the 50-ohm line, which is an advantage in obtaining a low resistance range required in linear array design<sup>3</sup>. To reduce experimental error in the measurements further, sag of the center conductor was prevented by putting the strip in tension rather than having it held in position by polyfoam supports. Finally, provisions were made for moving the center conductor transversely with respect to the longitudinal axis of the transmission line. In this way a wider range is obtained for offset of the slot transversely from the strip centerline, permitting the use of longer slots in the 3.9-inch wide line (see Figures 25 and 26).

Up to the present time, only a few slots have been measured in the 100-ohm line and the first results show the resonant resistances to have a value approximately half of those measured in the 50-ohm line. Figures 27 and 28 give normalized resistance and reactance as a function of offset for a 2.380-inch long, 1/8-inch wide, dielectric-loaded slot ( $\epsilon = 7.5$ ) for a number of frequencies near resonance. The dielectric material contained fiberglass and titanium dioxide and extended 1/8 inch above and below the slot cut in 1.32-inch thick plate, as shown in the sketch of Figure 27. From the original Smith Chart plot of the data (Figure 29), it may be noted that the resonant frequency (1095 mc/s) varies only slightly. The plot of resonant resistance as a function of offset (Figure 30) may then be used as the array design curve.

A forty-element array now is being constructed using the same guide and strip dimensions as the 100-ohm line, and the results will be available at a later date. An analysis of the impedance characteristics of transverse slots in a TEM mode transmission line has been made by Dr. N. Begovich and will also be published in the near future.

### BANDWIDTH

The "Q" of a slot is defined as  $Q = f_0/\Delta f$ , where  $f_0$  is the frequency at which the slot impedance is real, and  $\Delta f$  is the bandwidth between the frequencies at which the slot impedance falls to 0.707 times its maximum value. Figure 31 is a typical plot of absolute slot impedance as a function of frequency indicating the bandwidth of a slot. The effects of variation of various slot parameters on the Q of a transverse slot were studied. The following general trends can be recognized:

1. Reducing slot length by various methods of loading tends to increase the Q of the slot.
2. Widening the slot lowers the Q but increases the resonant frequency.



3. Increasing the dielectric constant of the loading material increases the Q of the slot.

The table below gives a comparison of Q's and resonant frequencies for various slot configurations.

	Resonant Frequency (mc/s)	Q	Line Characteristic Impedance (Ohms)
5" x 1/6" straight unloaded	1200	24	50
3" x 1/8" straight, dielectric loaded, $\epsilon = 7.2$	1150	33	100
3" x 1/16" x 1" diameter dumbbells	1200	37	50
2-1/2" x 3/16" x 7/8" diameter dumbbells, dielectric in straight section only, $\epsilon = 7.4$	1220	27	50
3" x 5/8" straight, dielectric loaded, $\epsilon = 7.2$	1390	14	100
2" x 1/16" x 1/2" diameter dumbbells, dielectric in straight section only, $\epsilon = 7.4$	1000	110	50
1-5/8" x 1/16" x 1/2" diameter dumbbells, dielectric in straight section only, $\epsilon = 7.4$	1300	118	50

These results indicate that, with the proper choice of slot width, dielectric material, and dumbbell size, the over-all length of a slot can be reduced appreciably while still keeping it comparatively broadband as compared with an unloaded slot. Further investigation of broadbanding and, in particular, the characteristics of multiple slots, are covered by Ehrlich, Reed, and Short<sup>4</sup>.

### **ACKNOWLEDGMENTS**

The authors wish to thank A. R. Margolin and R. H. Reed for the design of the two test transmission lines.

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4. M. Ehrlich, R. H. Reed, J. Short, Hughes Aircraft Company Termination Memorandum, "Broadbanding Slot Study."

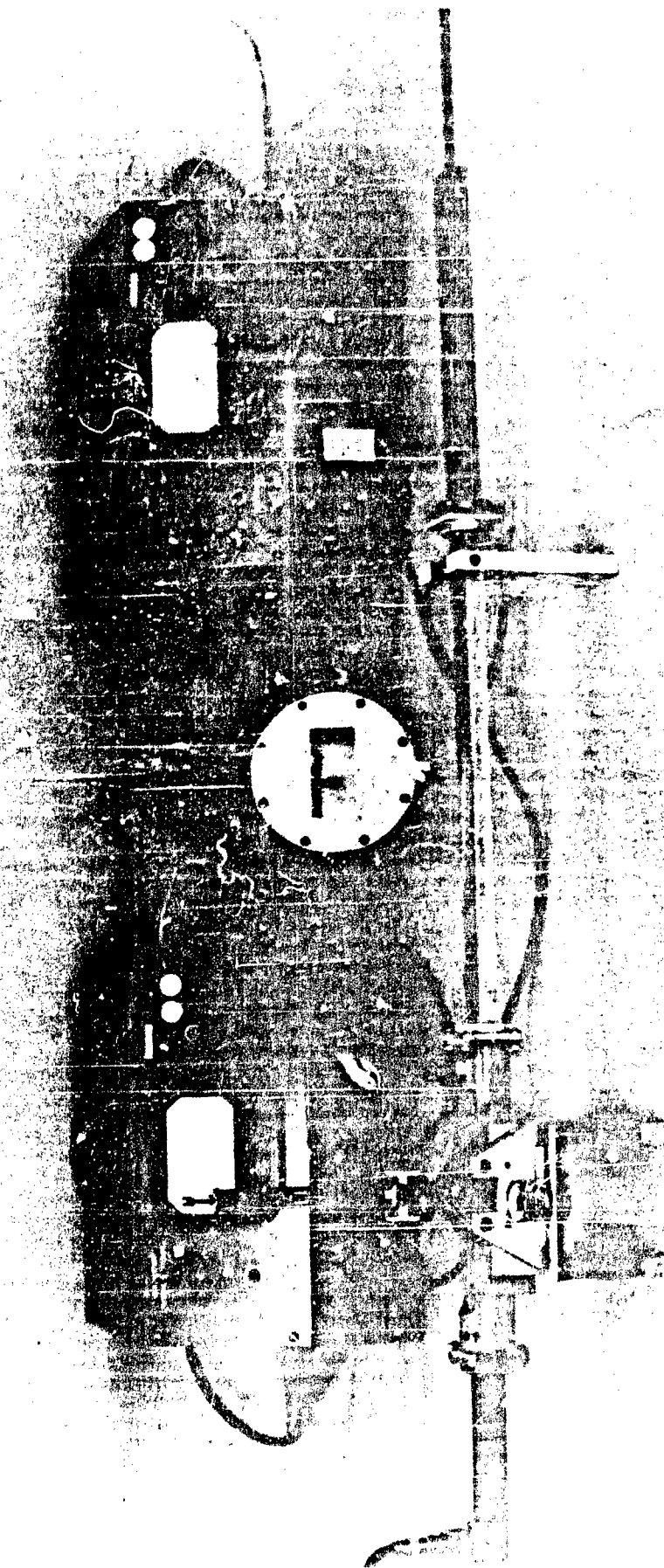


FIGURE 1. IMPEDANCE MEASURING EQUIPMENT

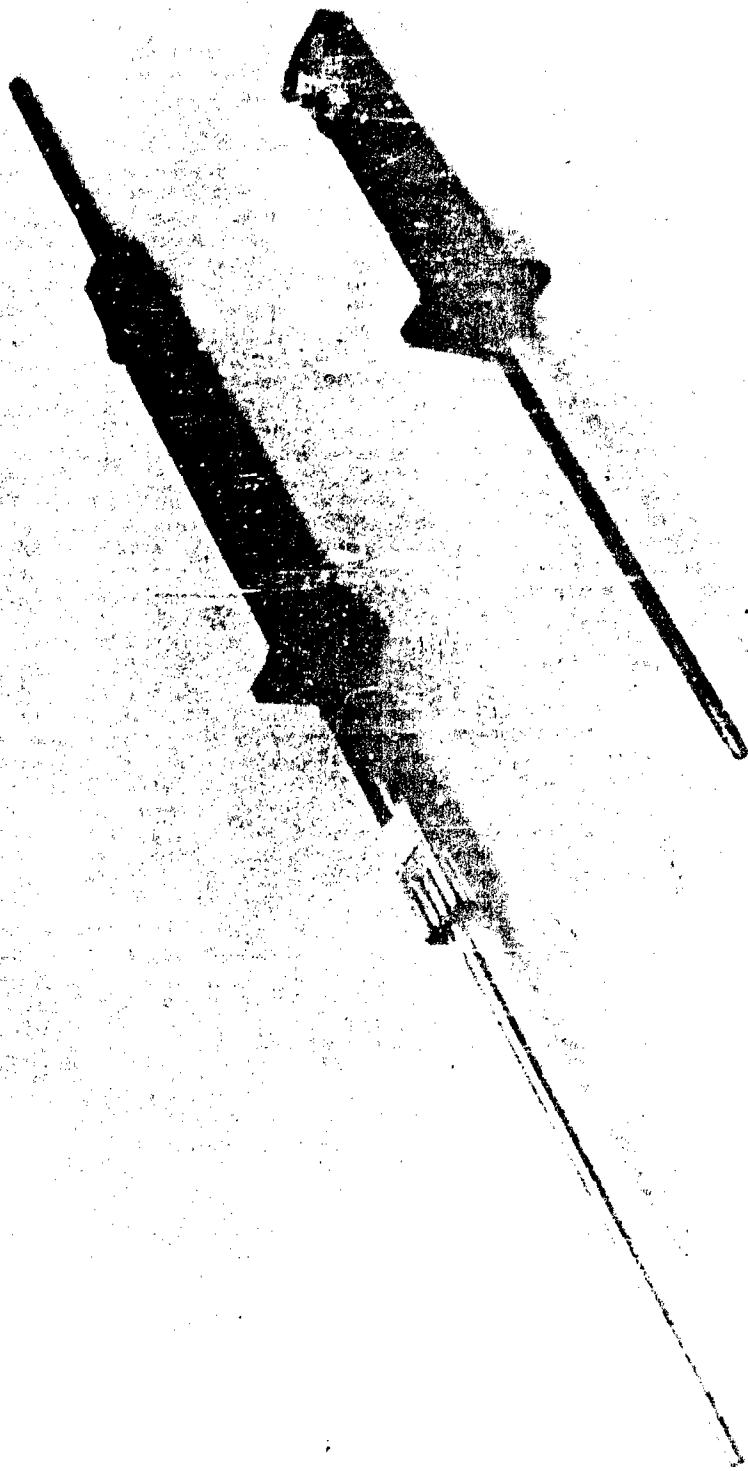


FIGURE 2. SHORT-CIRCUITING PLUNGER ASSEMBLY AND  
TYPE N CONNECTOR ATTACHMENT

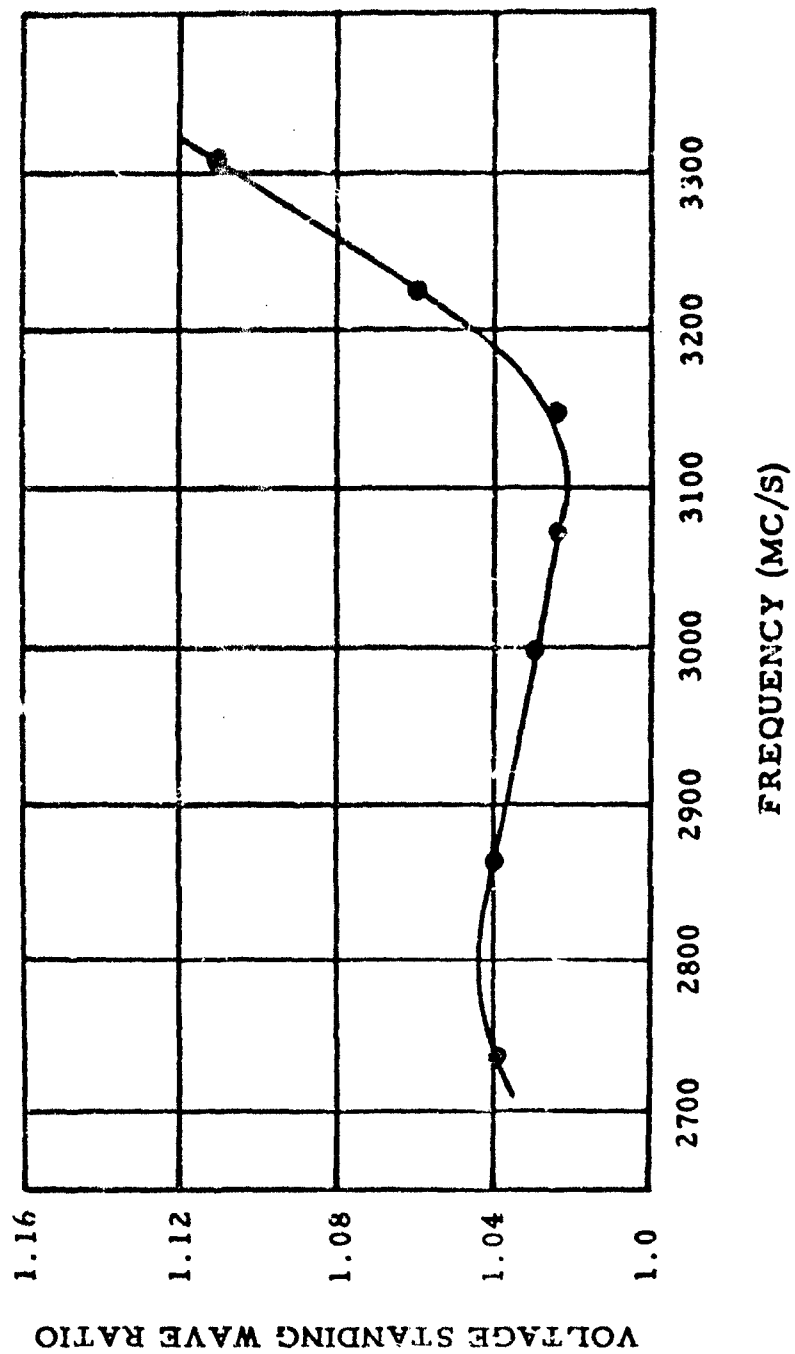


FIGURE 3. VSWR VS FREQUENCY FOR TEM MATCHED TERMINATION

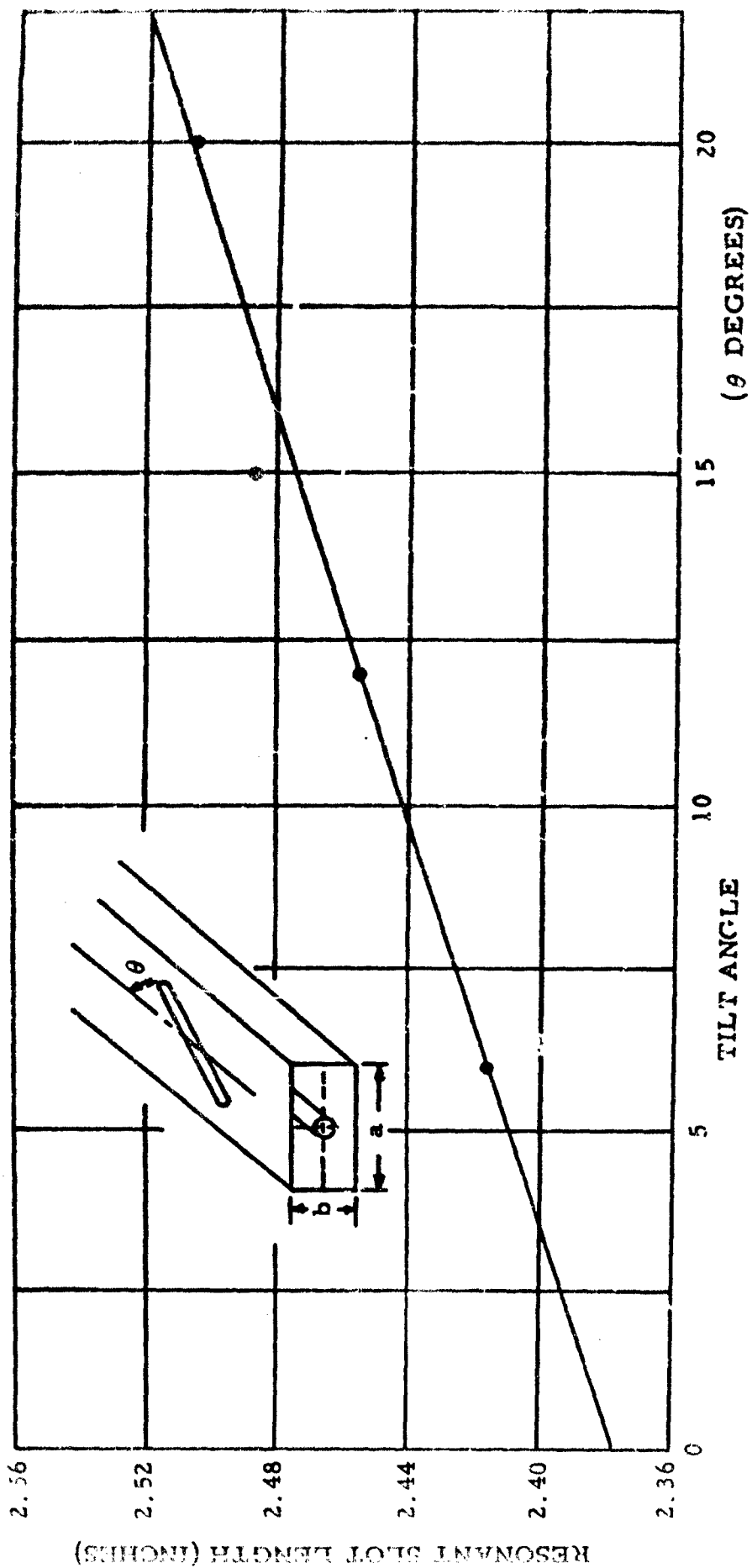


FIGURE 4. LENGTH VS  $\theta$  FOR SERIES SLOT IN TEM LINE AT 3000 MC/S

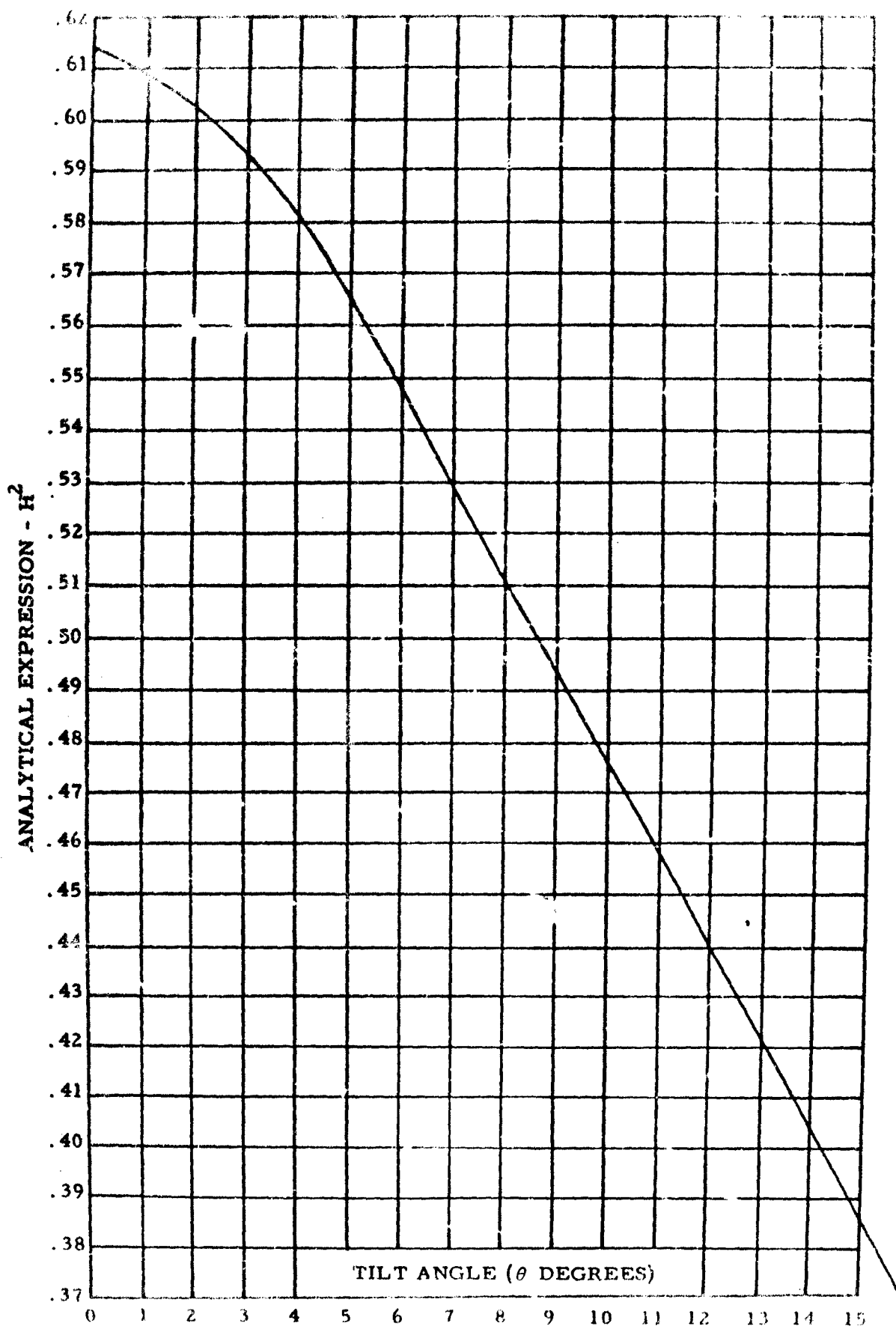


FIGURE 5.  $H^2$  VS  $\theta$  FOR TEM LINE AT 3000 MC/S

$\theta = 20^\circ$   
 $H^2 = 0.291$

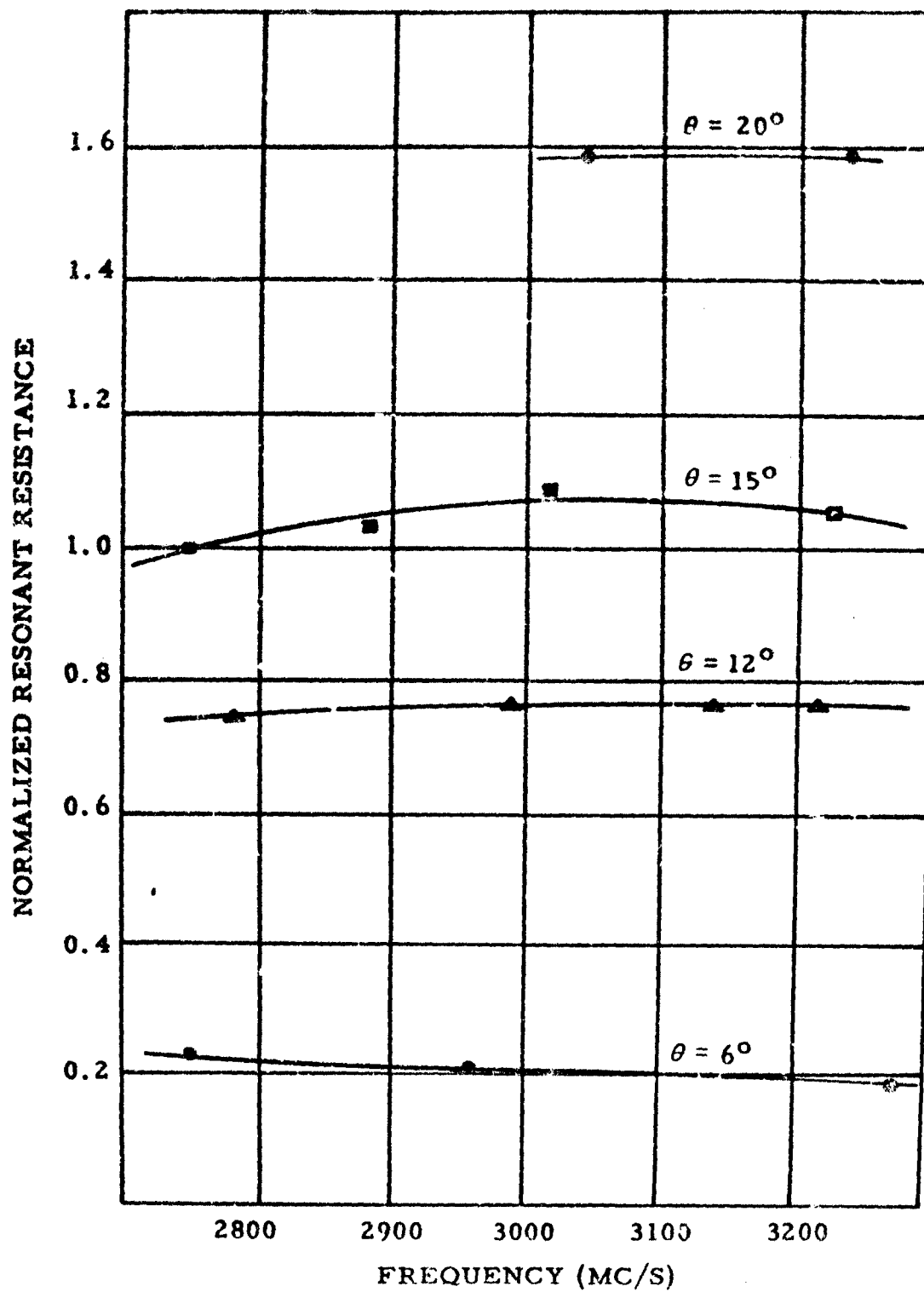


FIGURE 6. RESISTANCE VS FREQUENCY FOR TEM SLOTS



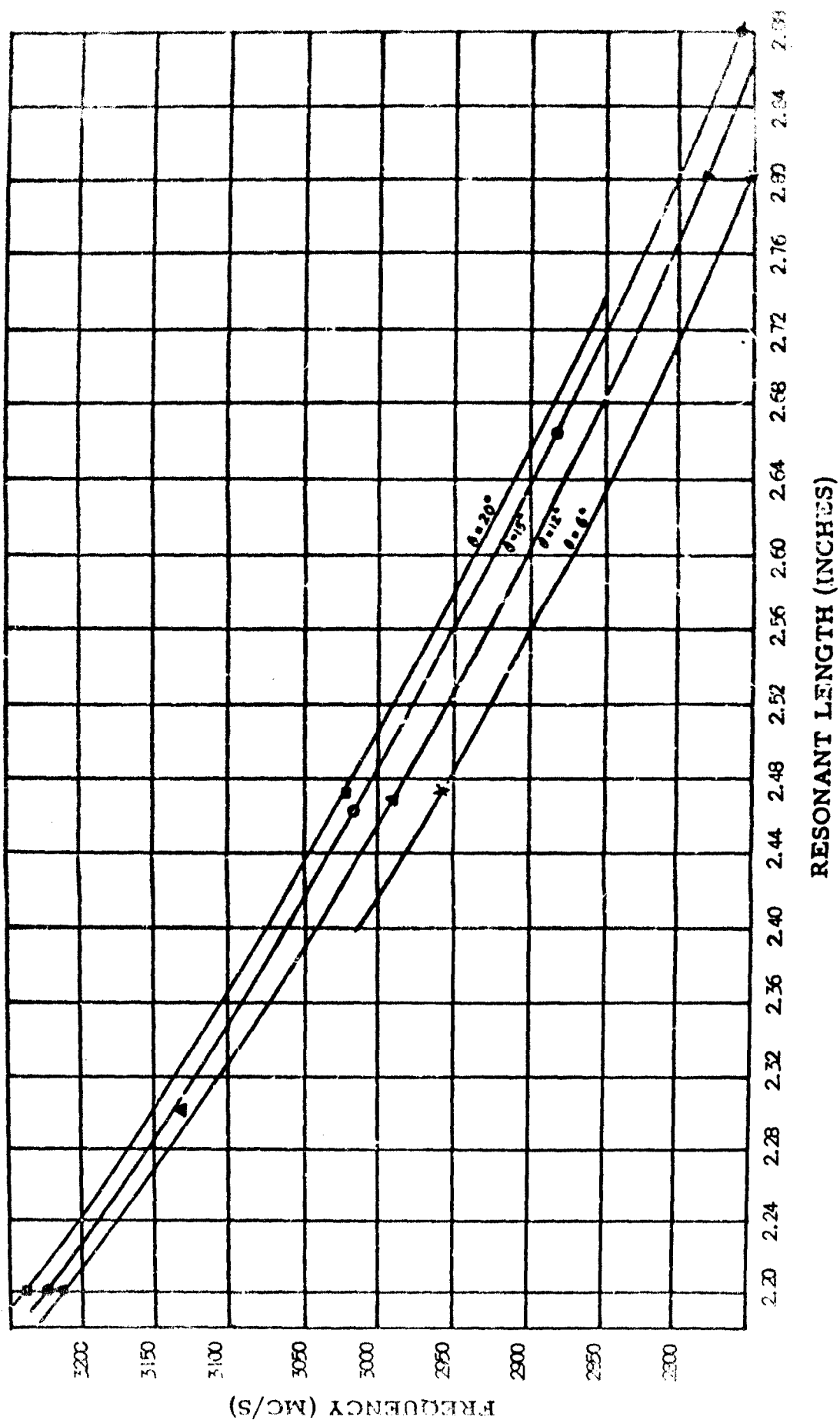


FIGURE 7. FREQUENCY VS RESONANT LENGTH FOR TEM SLOTS

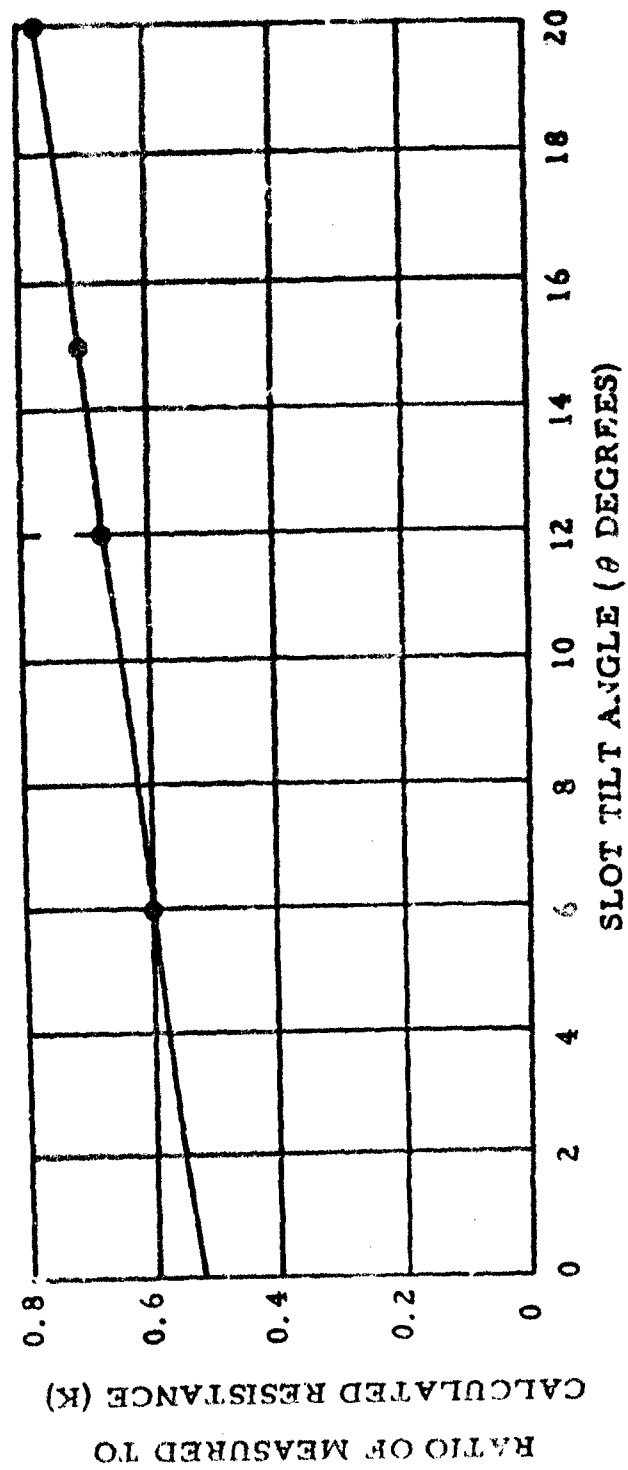


FIGURE 8. DISCREPANCY BETWEEN MEASURED AND THEORETICAL RESISTANCES

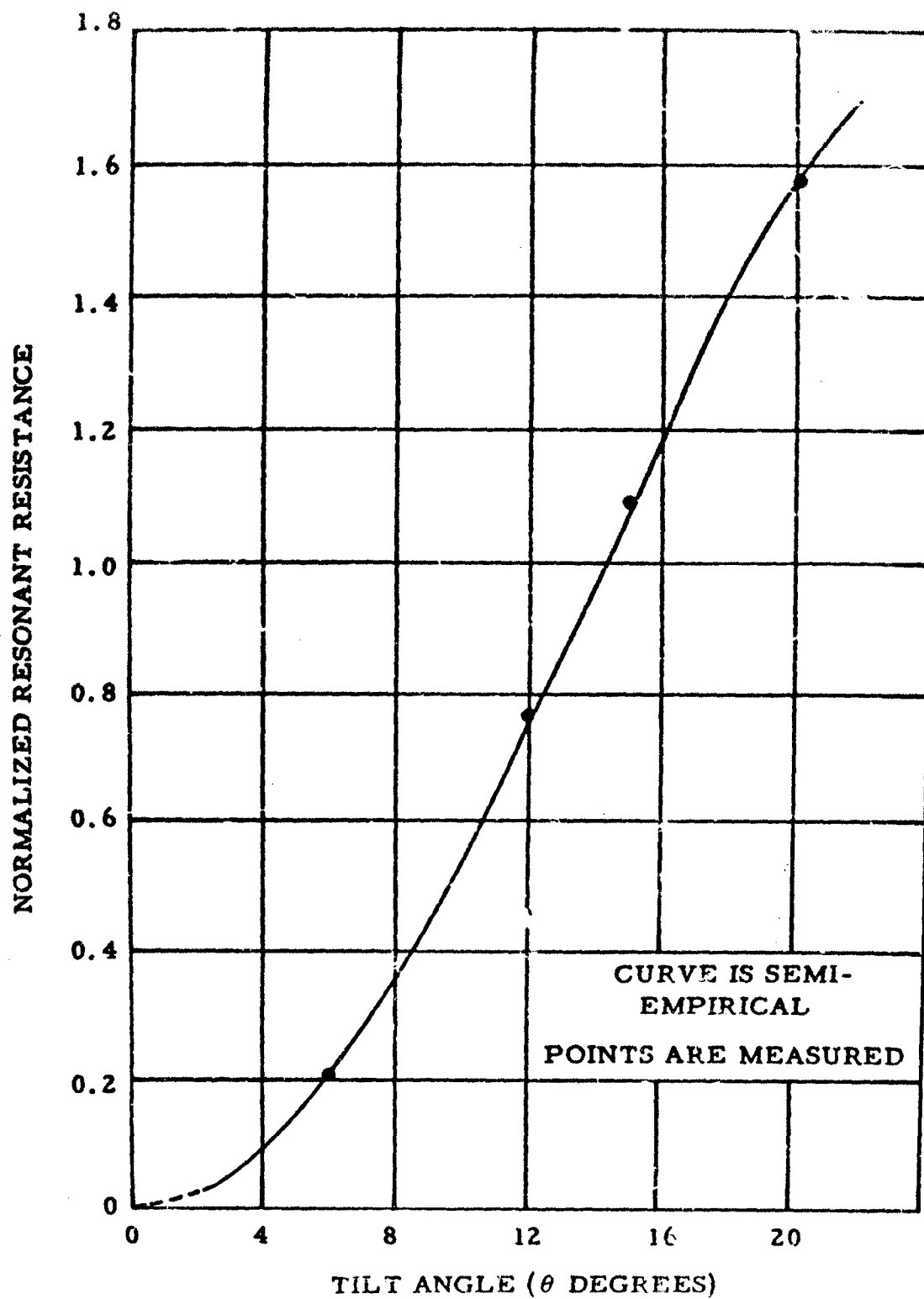


FIGURE 9. RESISTANCE VS TILT ANGLE FOR TEM SLOTS

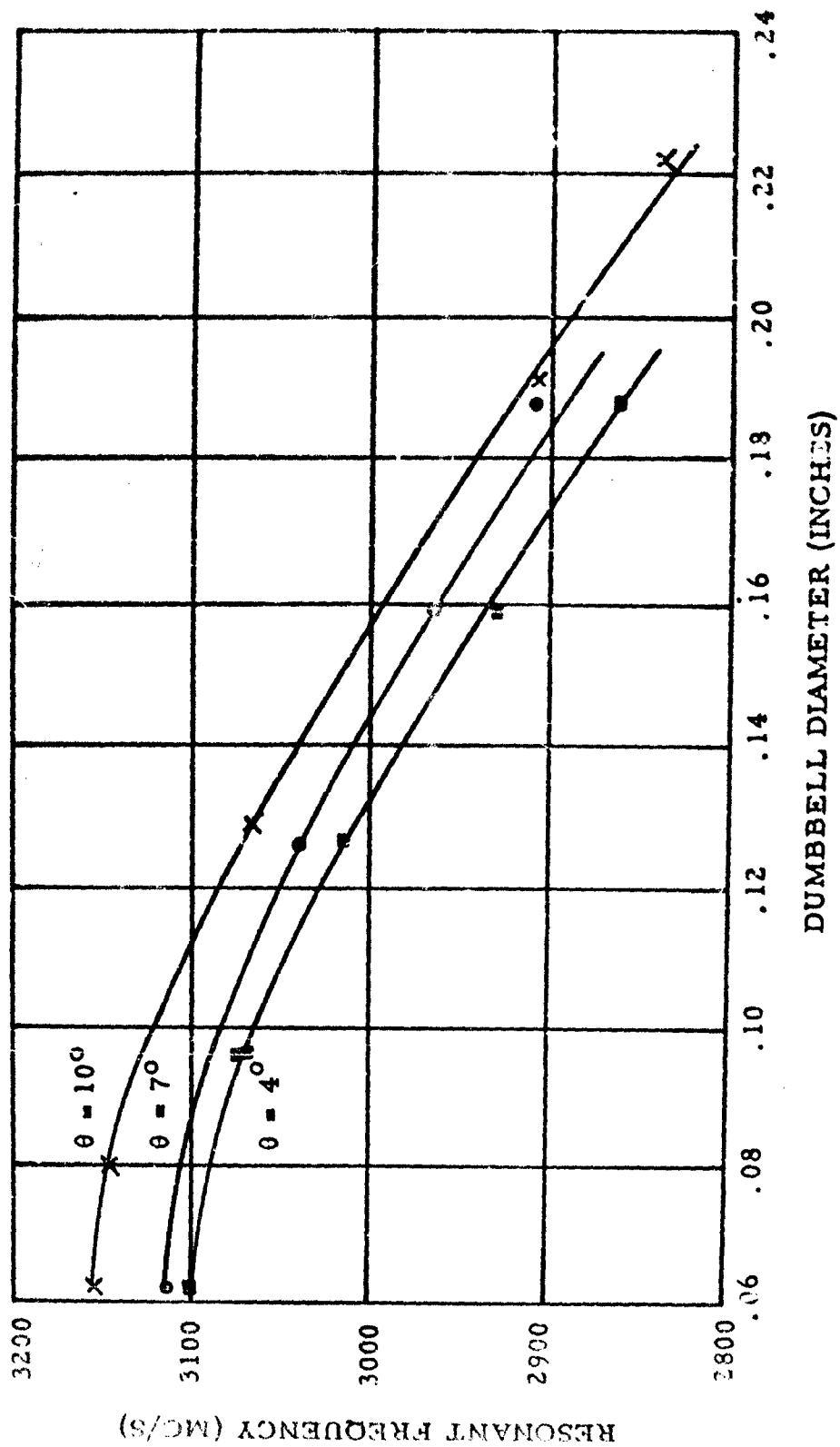


FIGURE 10. RESONANT FREQUENCY VS DUMBELL  
DIAMETER FOR TEM SLOTS  
SLOT LENGTH = 2.284 INCHES

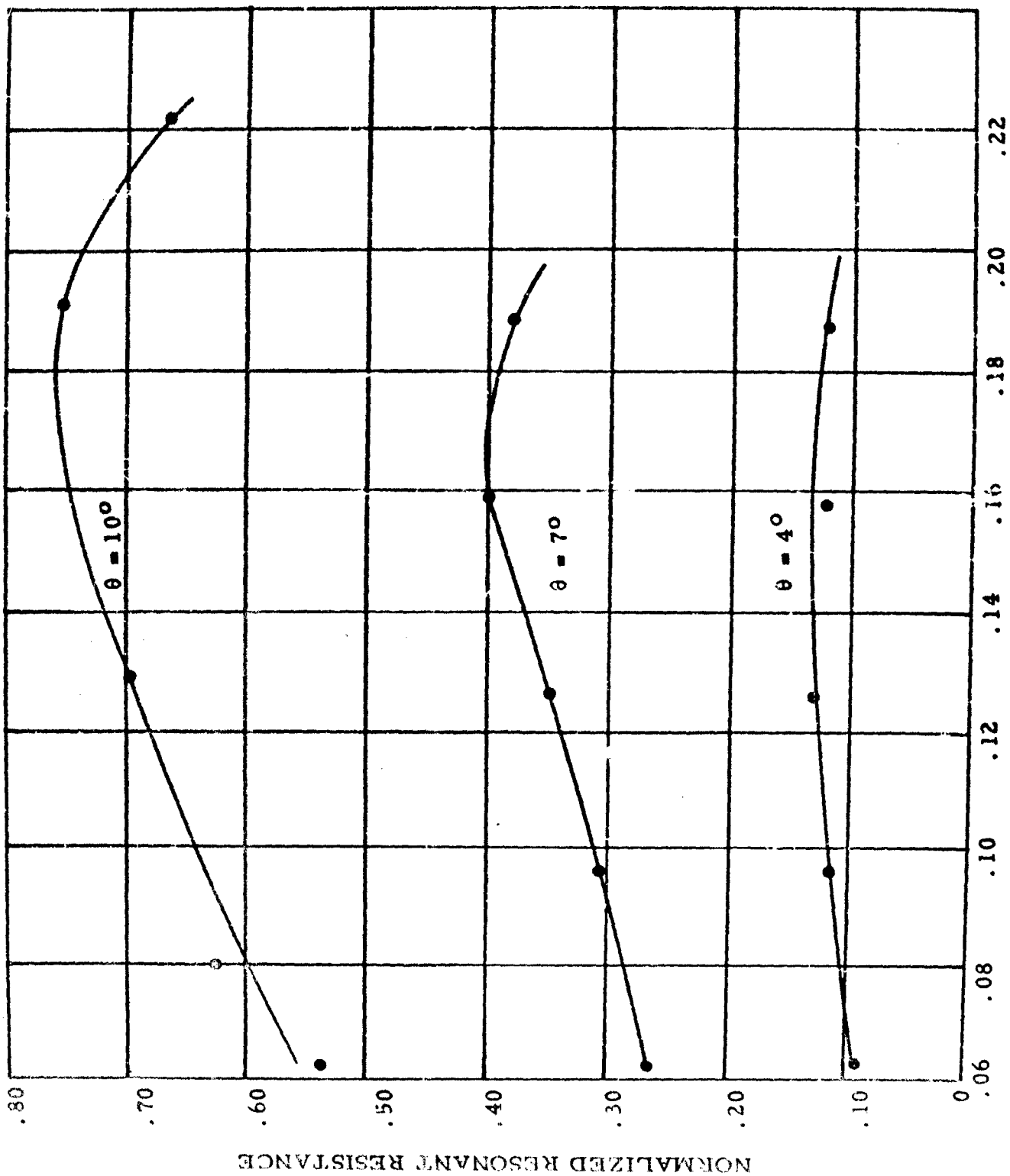


FIGURE 11. RESISTANCE VS DUMBELL DIAMETER FOR TEM SLOTS  
 DUMBELL DIAMETER (INCHES)  
 SLOT LENGTH = 2.284 INCHES

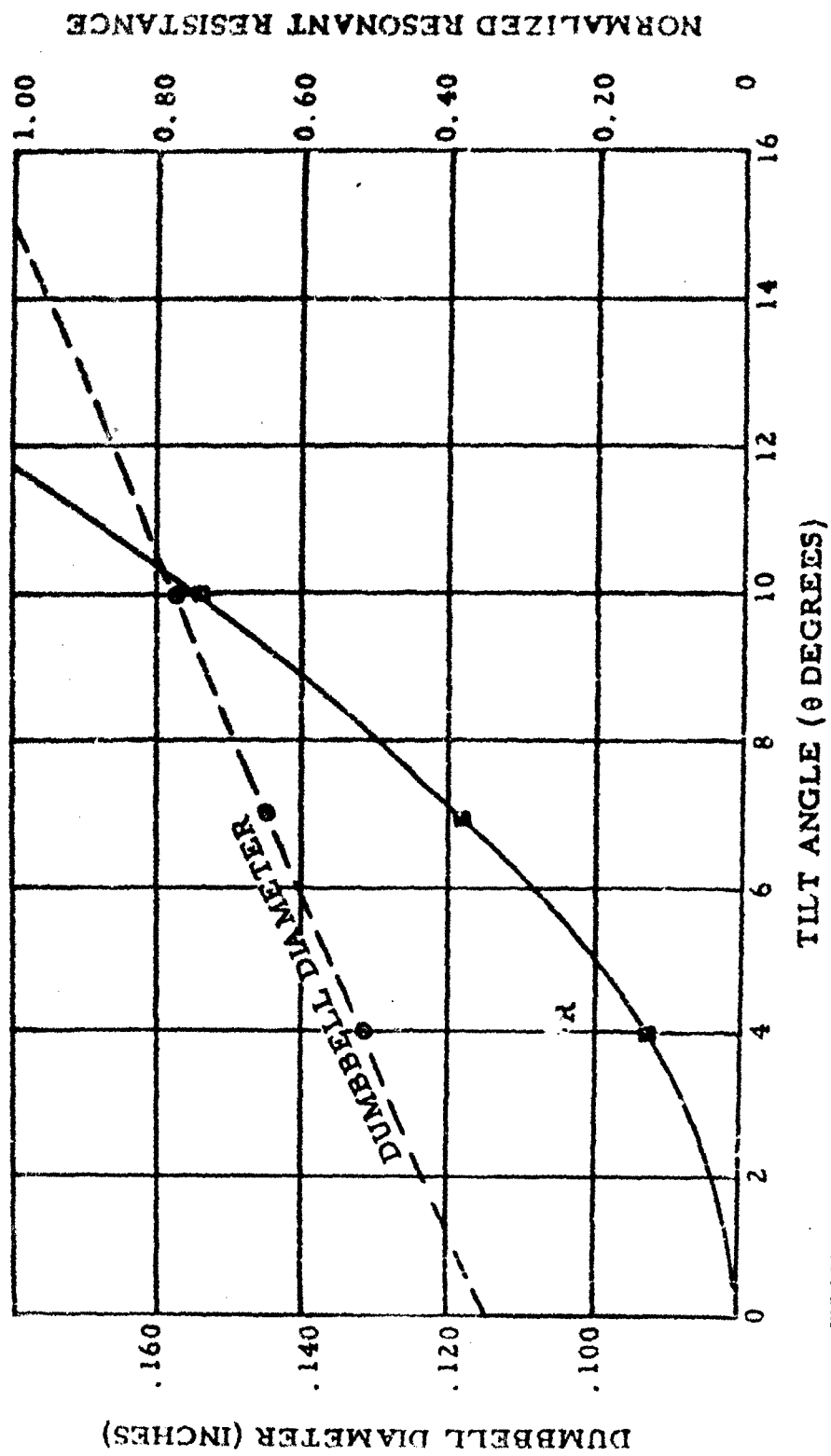


FIGURE 12. RESISTANCE AND DUMBELL DIAMETER VS  $\theta$  AT 3000 MC/S  
FOR TEM SLOFS. SLOT LENGTH = 2.284"



FIGURE 13. SIXTEEN-ELEMENT TEM ARRAY

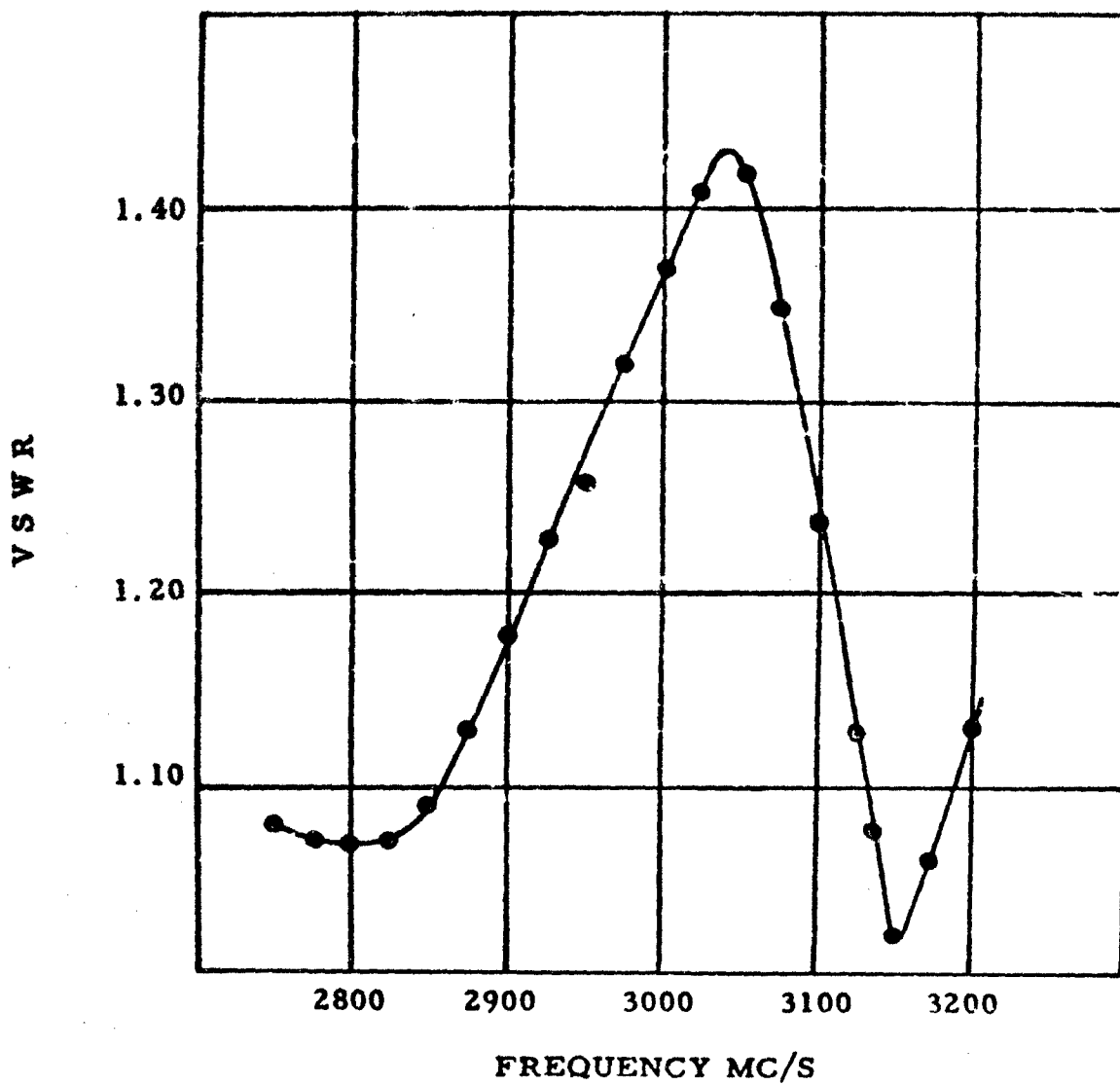


FIGURE 14. VOLTAGE STANDING WAVE RATIO  
OF TEM ARRAY AND LOAD



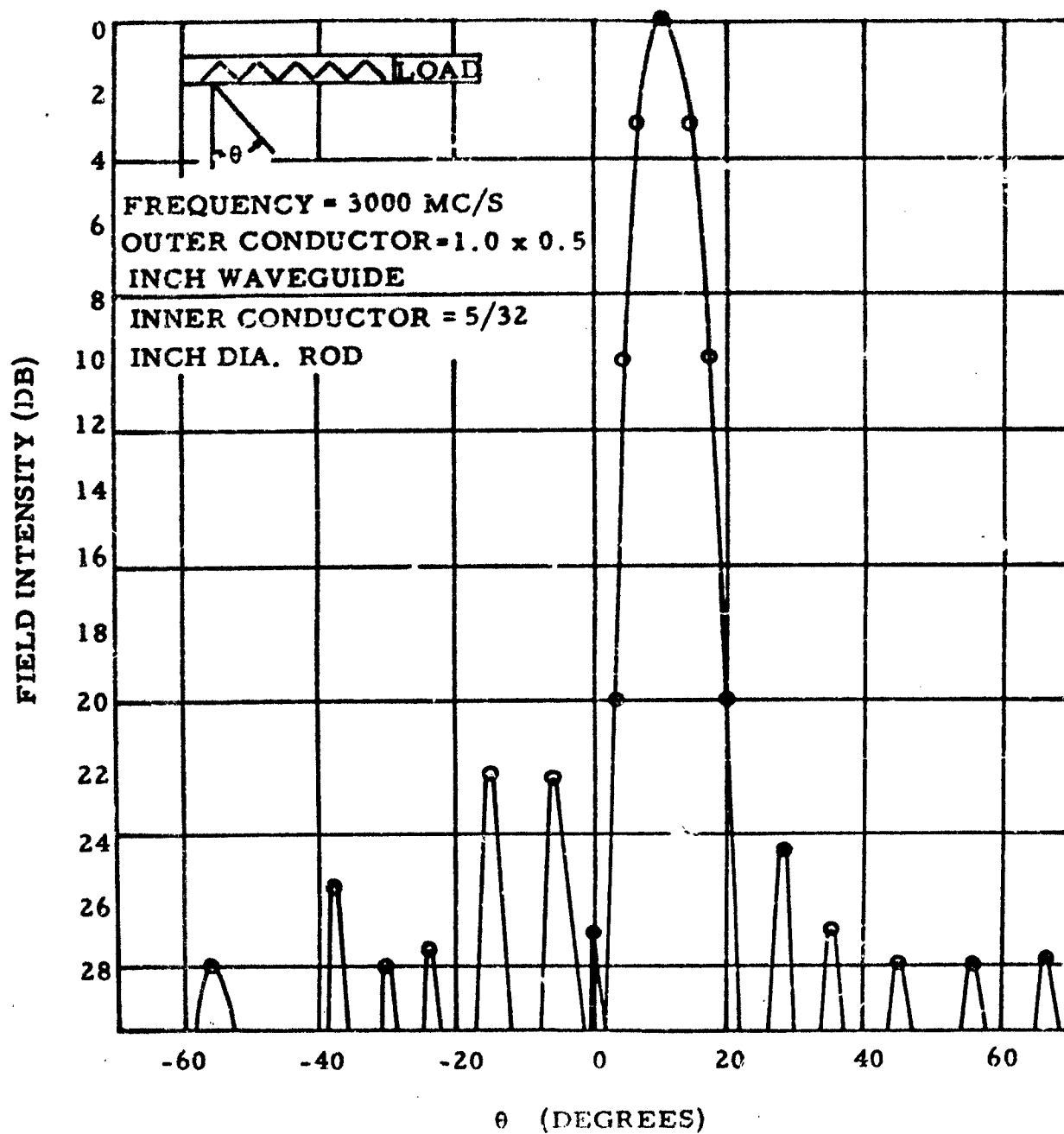


FIGURE 15. RADIATION PATTERN OF 16-ELEMENT TEM ARRAY

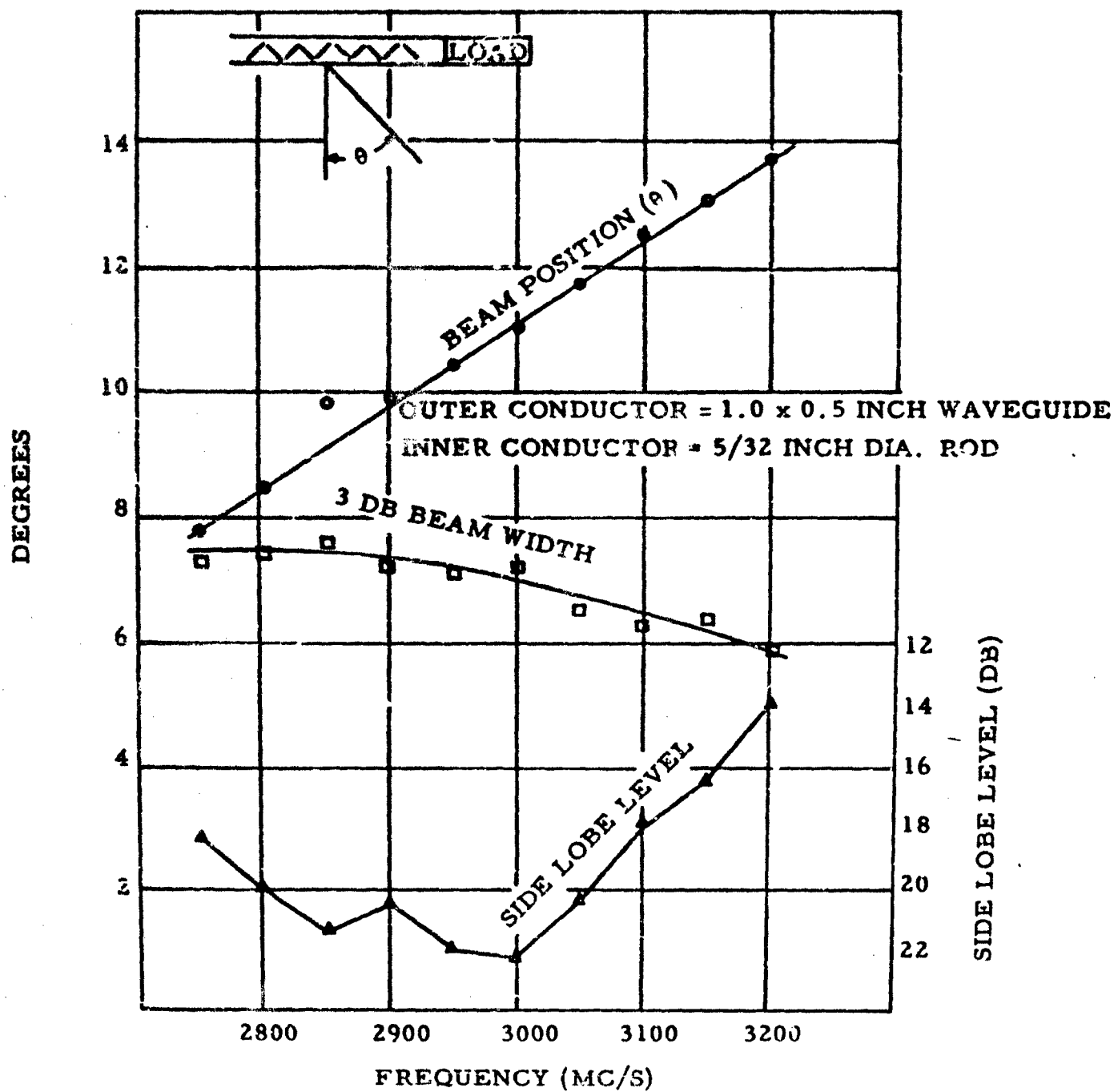
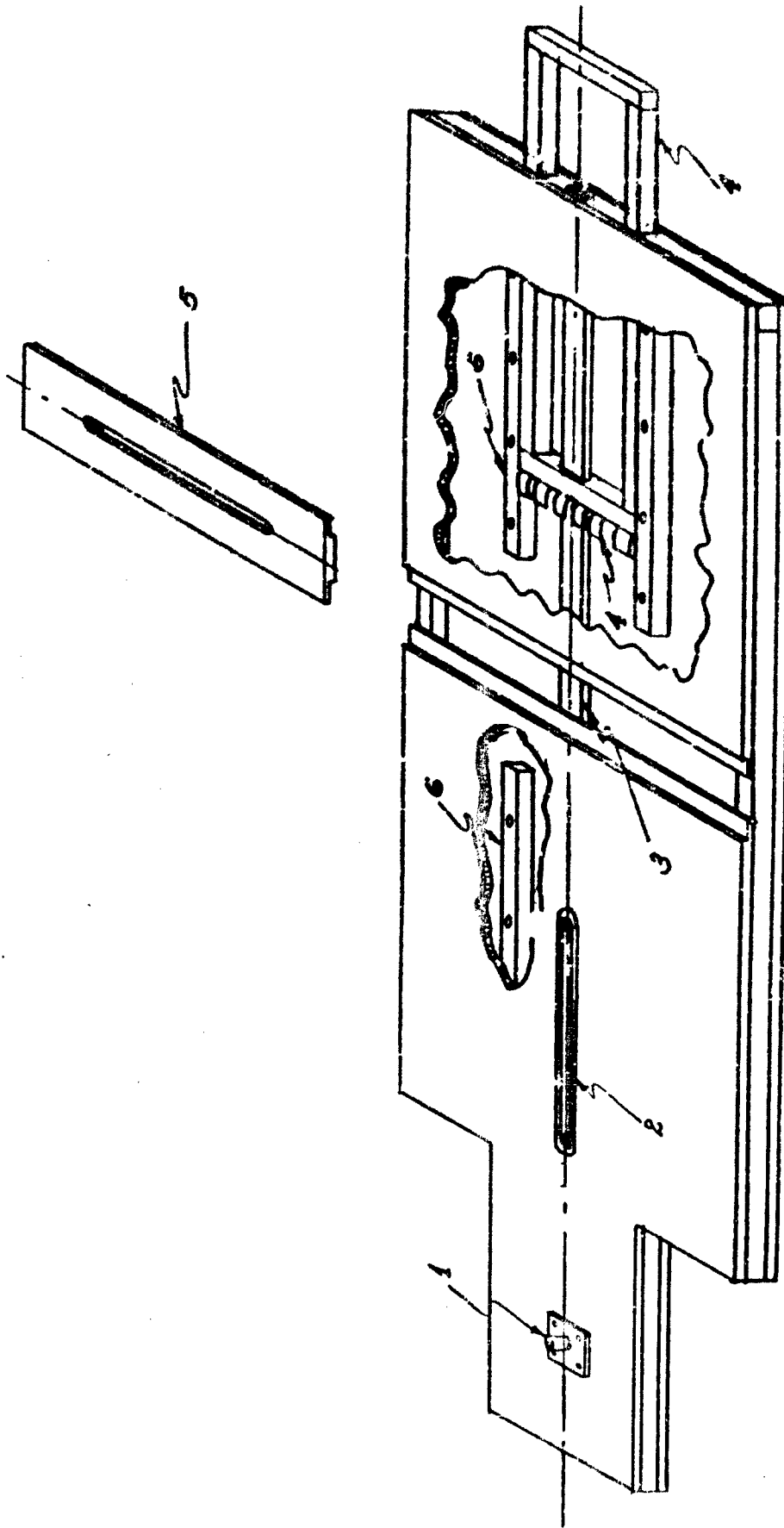


FIGURE 16. MAXIMUM SIDE LOBES, BEAM WIDTH AND BEAM POSITION OF 16-ELEMENT TEM ARRAY



- |                                        |                                   |
|----------------------------------------|-----------------------------------|
| 1. Input Connection.                   | 4. Moving Contacting Short.       |
| 2. Slotted Line (For Traveling Probe). | 5. Test Slot.                     |
| 3. Center Conductor.                   | 6. Spacers (Eliminate TE10 Mode). |

Figure 17 TEM - STRIP TRANSMISSION LINE

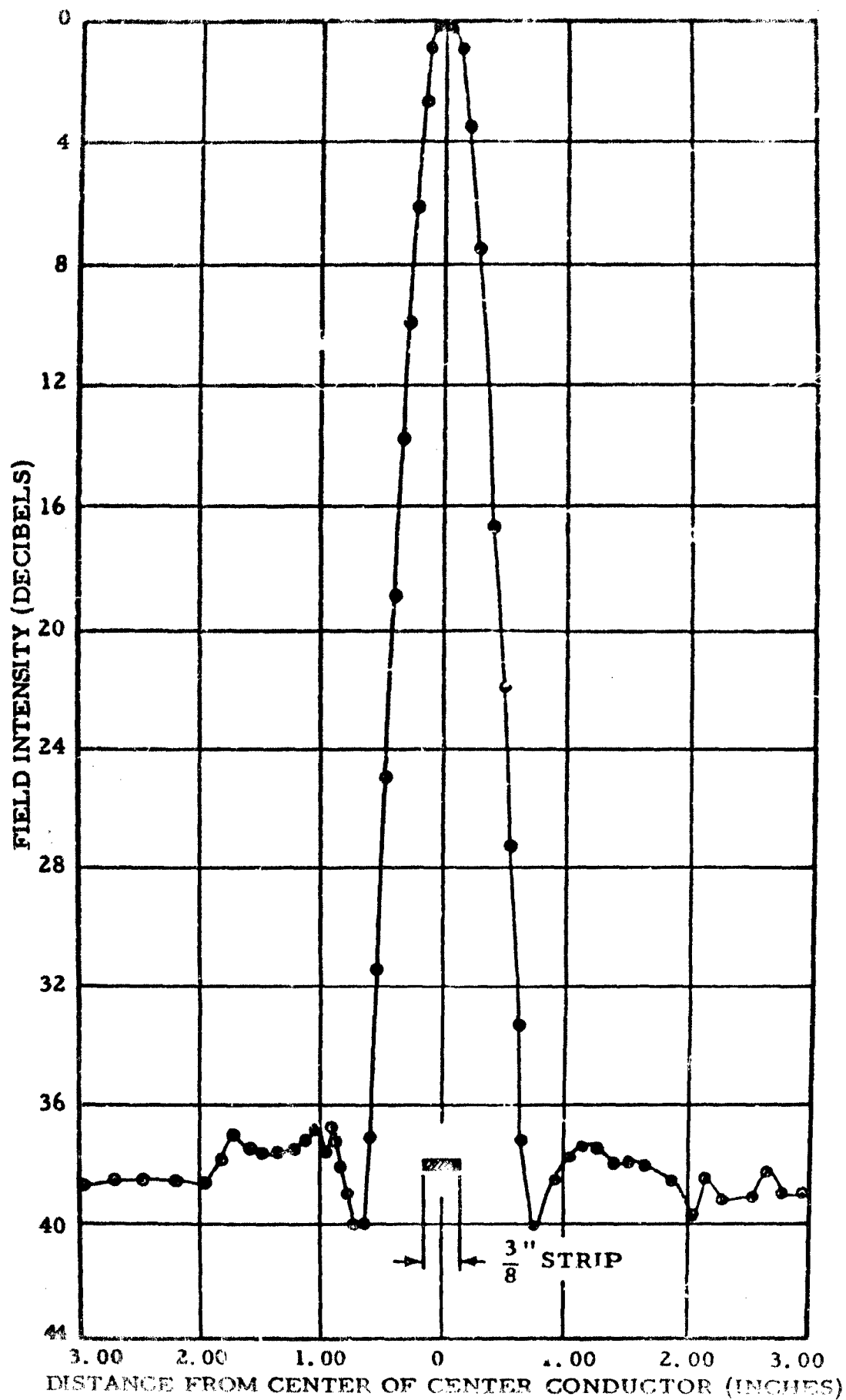


FIGURE 18. FIELD DISTRIBUTION ACROSS TEM STRIP LINE

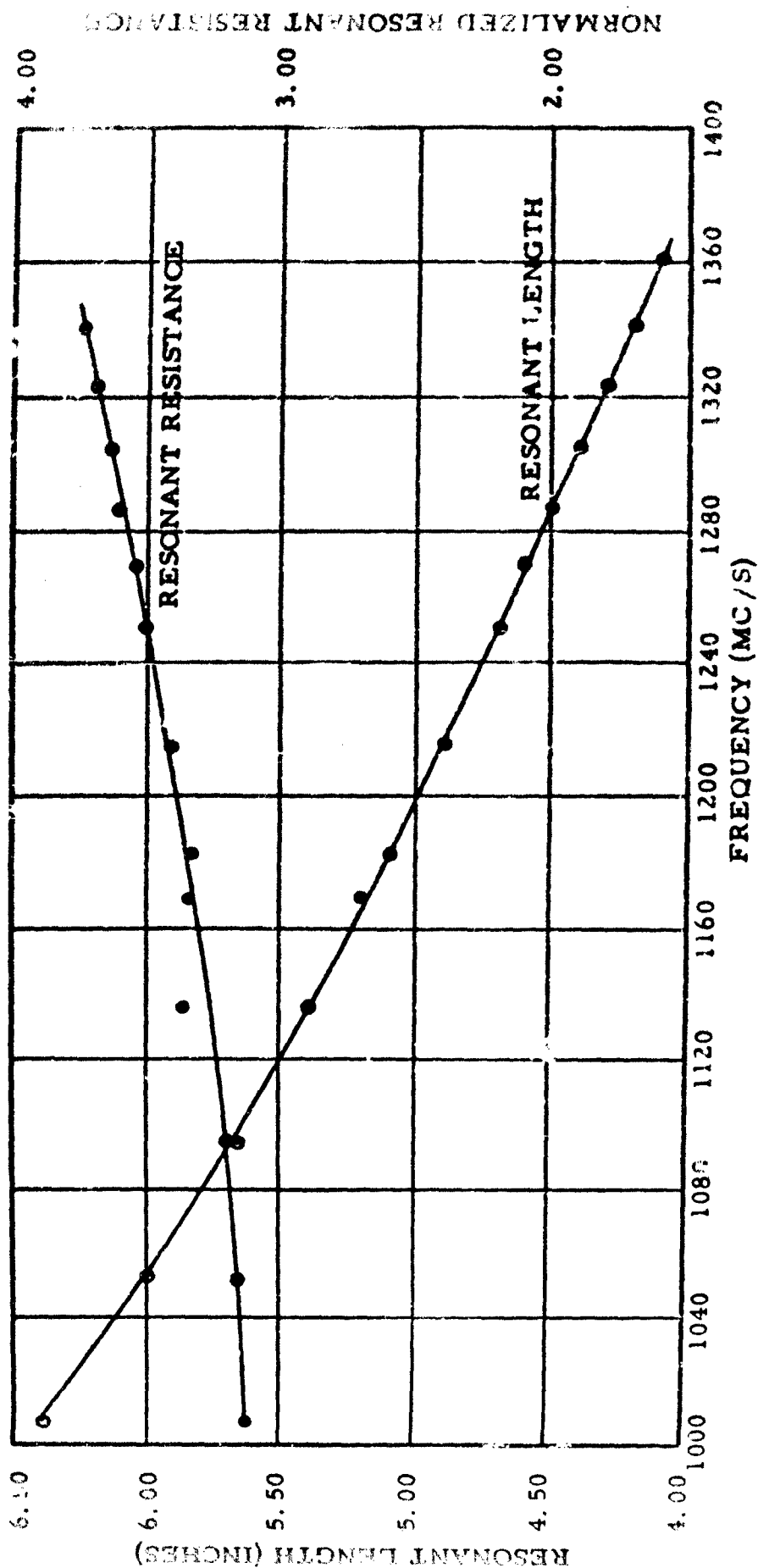


FIGURE 19. RESONANT LENGTH AND RESONANT RESISTANCE VS FREQUENCY  
FOR 1/16"-WIDE TRANSVERSE SLOT IN TEM STRIP LINE.

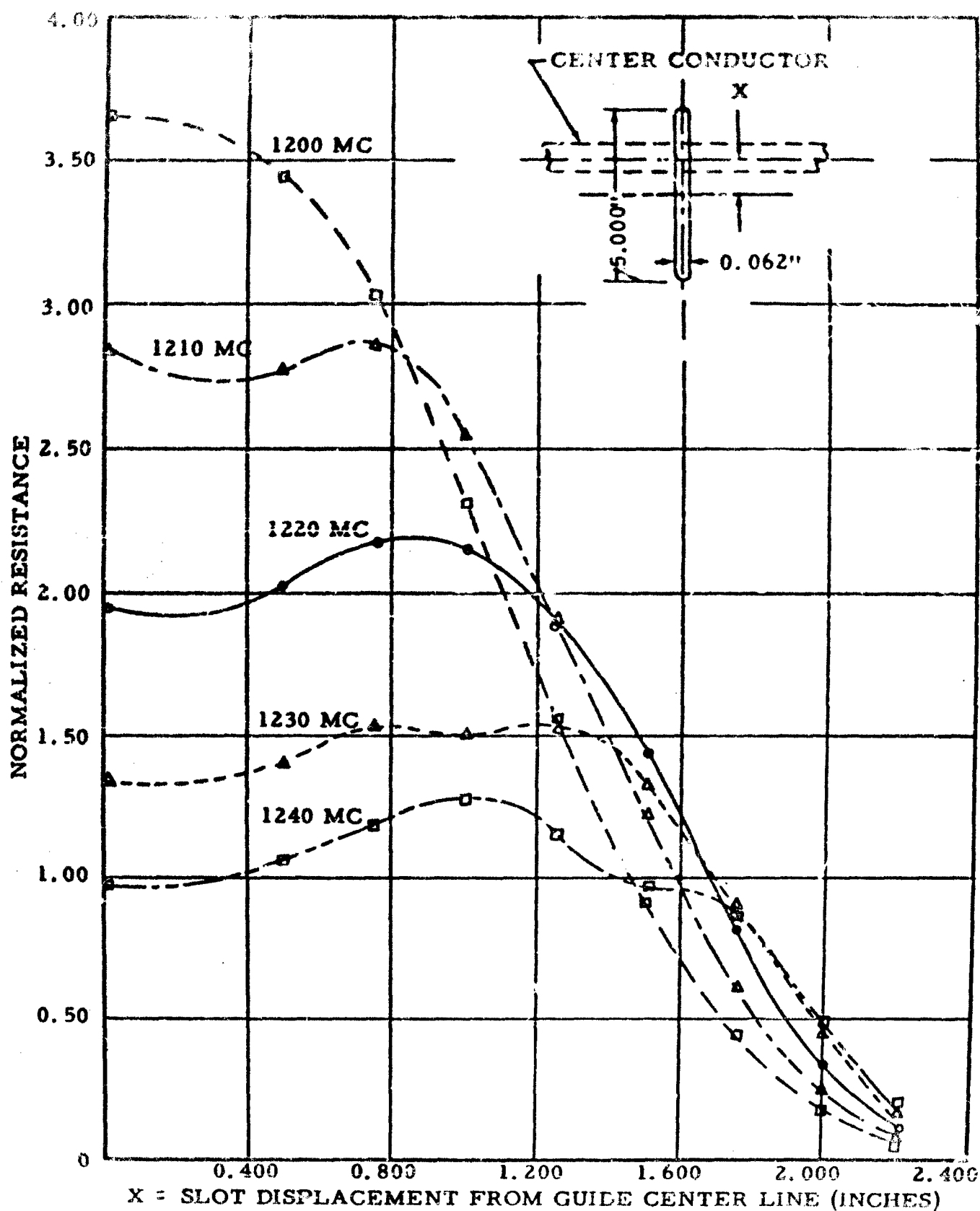


FIGURE 20. NORMALIZED RESISTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY FOR TRANSVERSE SLOT AS MEASURED IN THE 50-OHM TEM LINE.

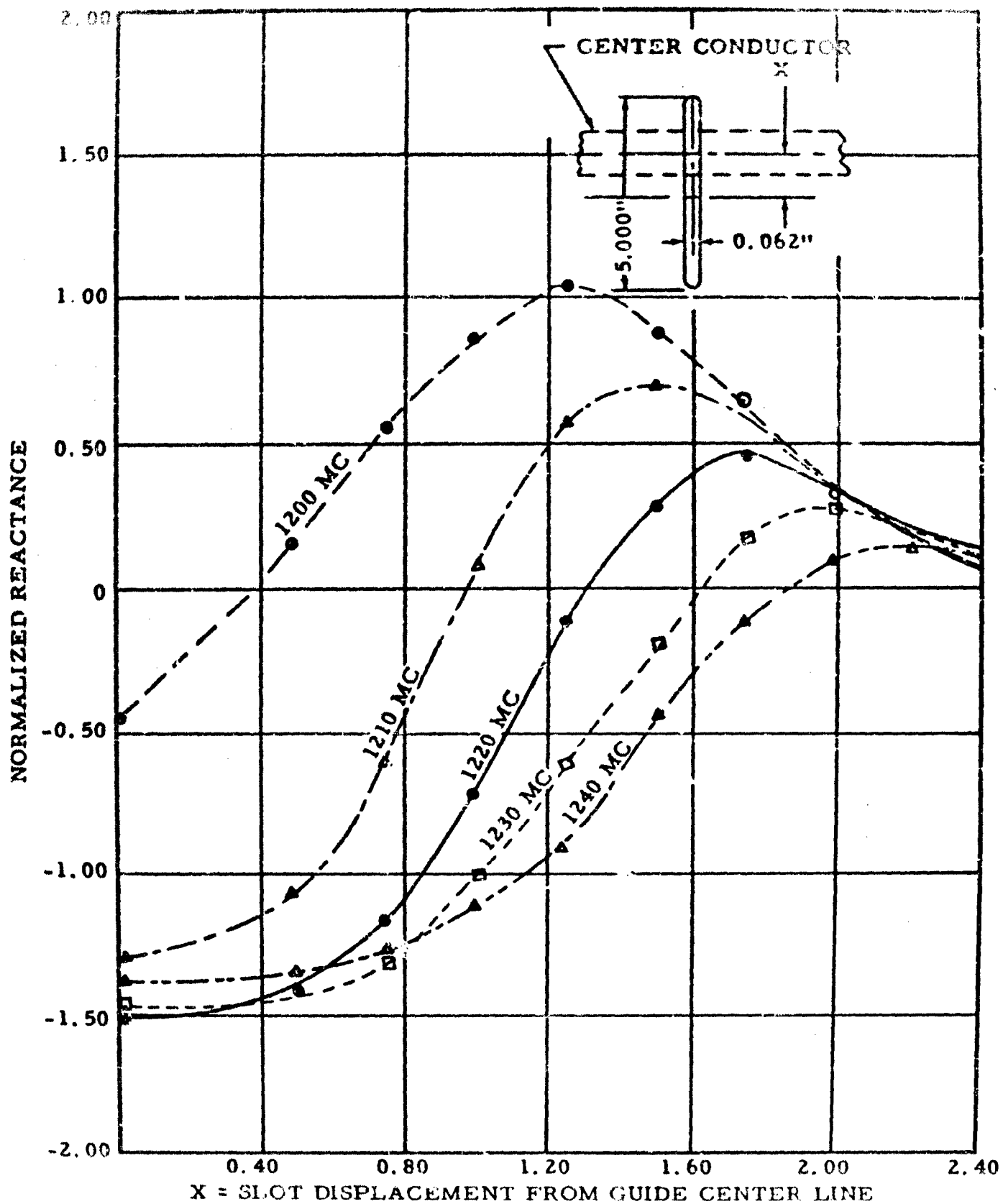


FIGURE 21. NORMALIZED REACTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY FOR TRANSVERSE SLOT AS MEASURED IN 50-OHM TEM LINE.

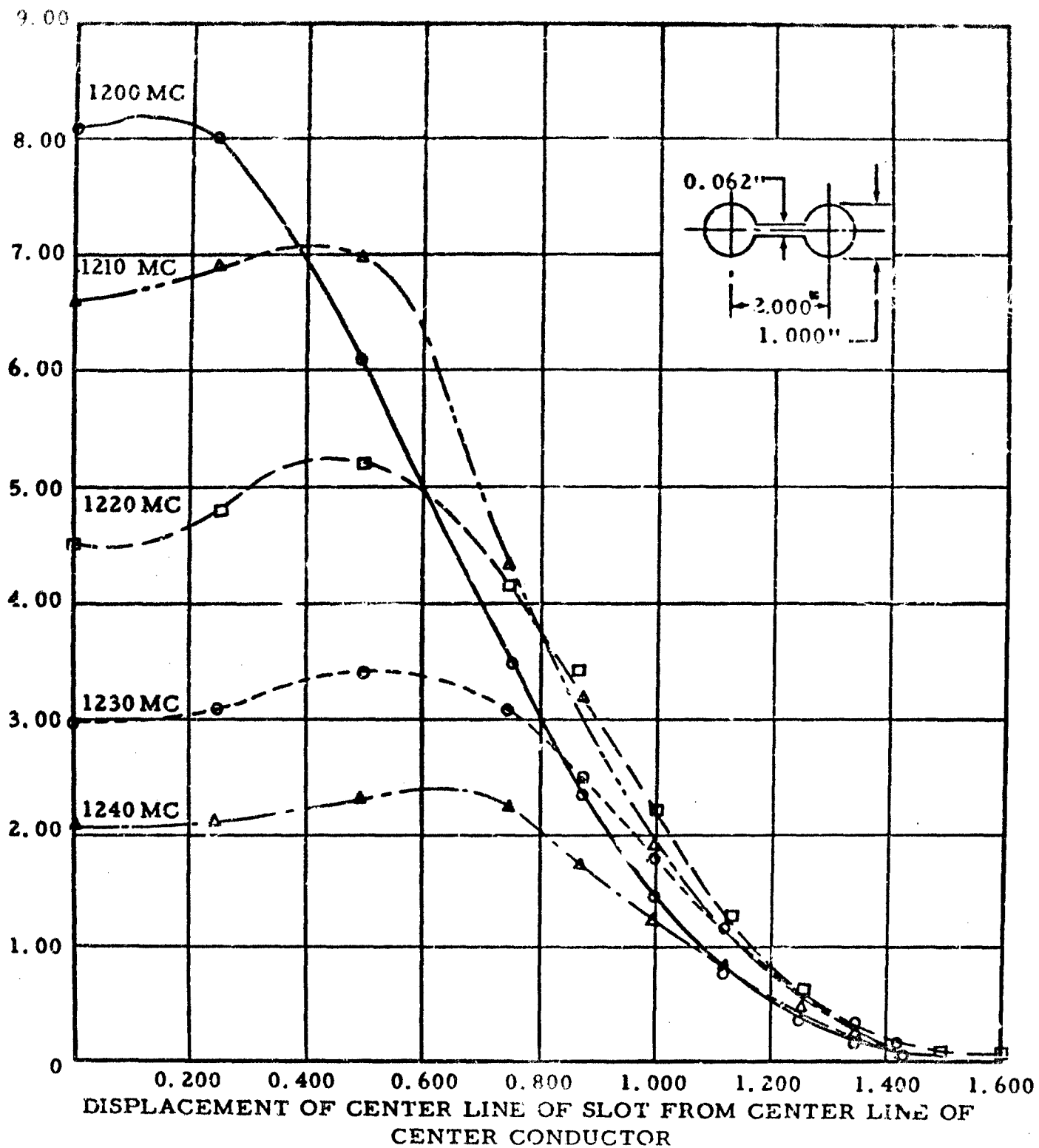


FIGURE 22. NORMALIZED RESISTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY AS MEASURED IN THE 50-OHM TEM LINE.



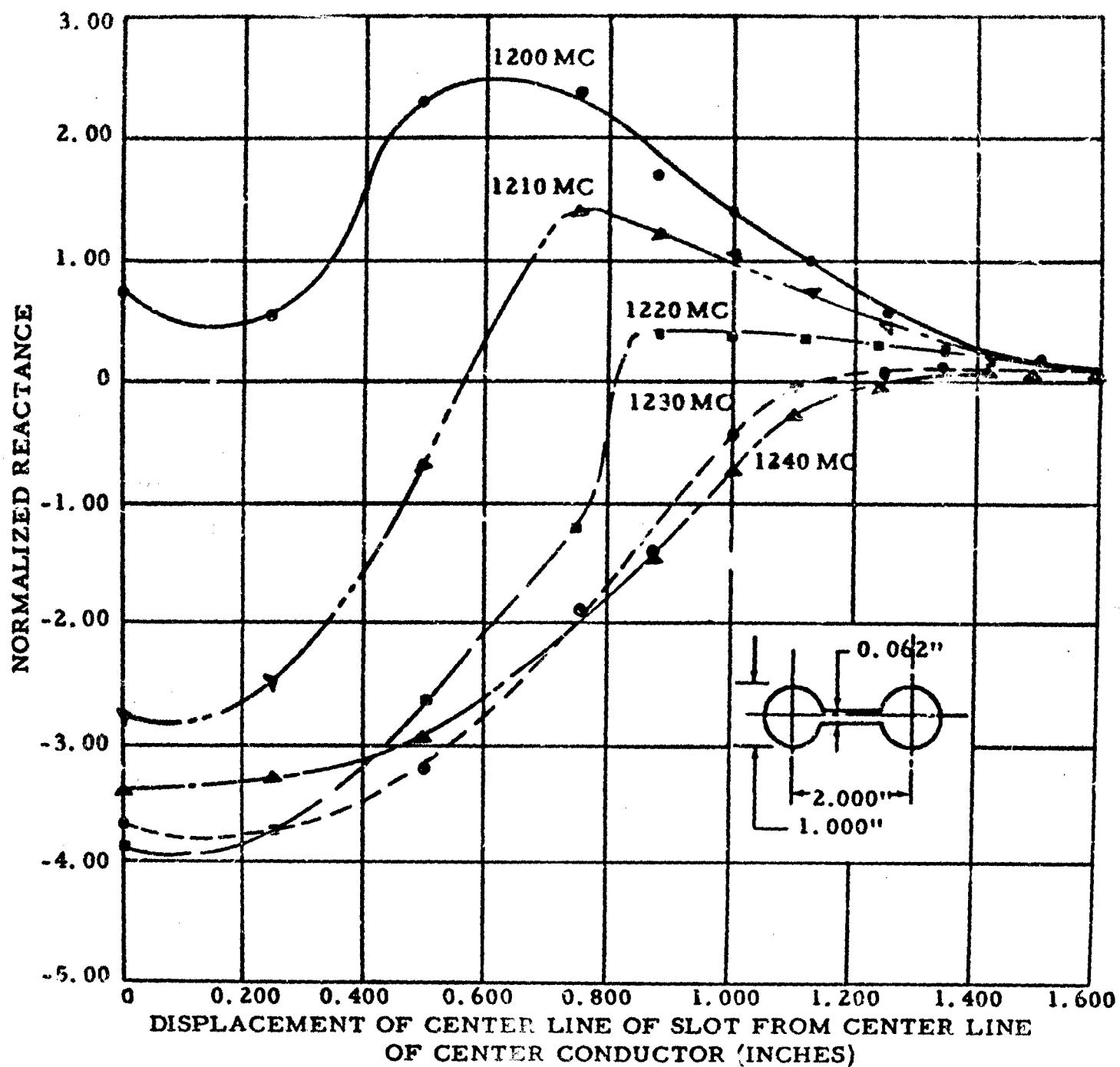


FIGURE 23. NORMALIZED REACTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY

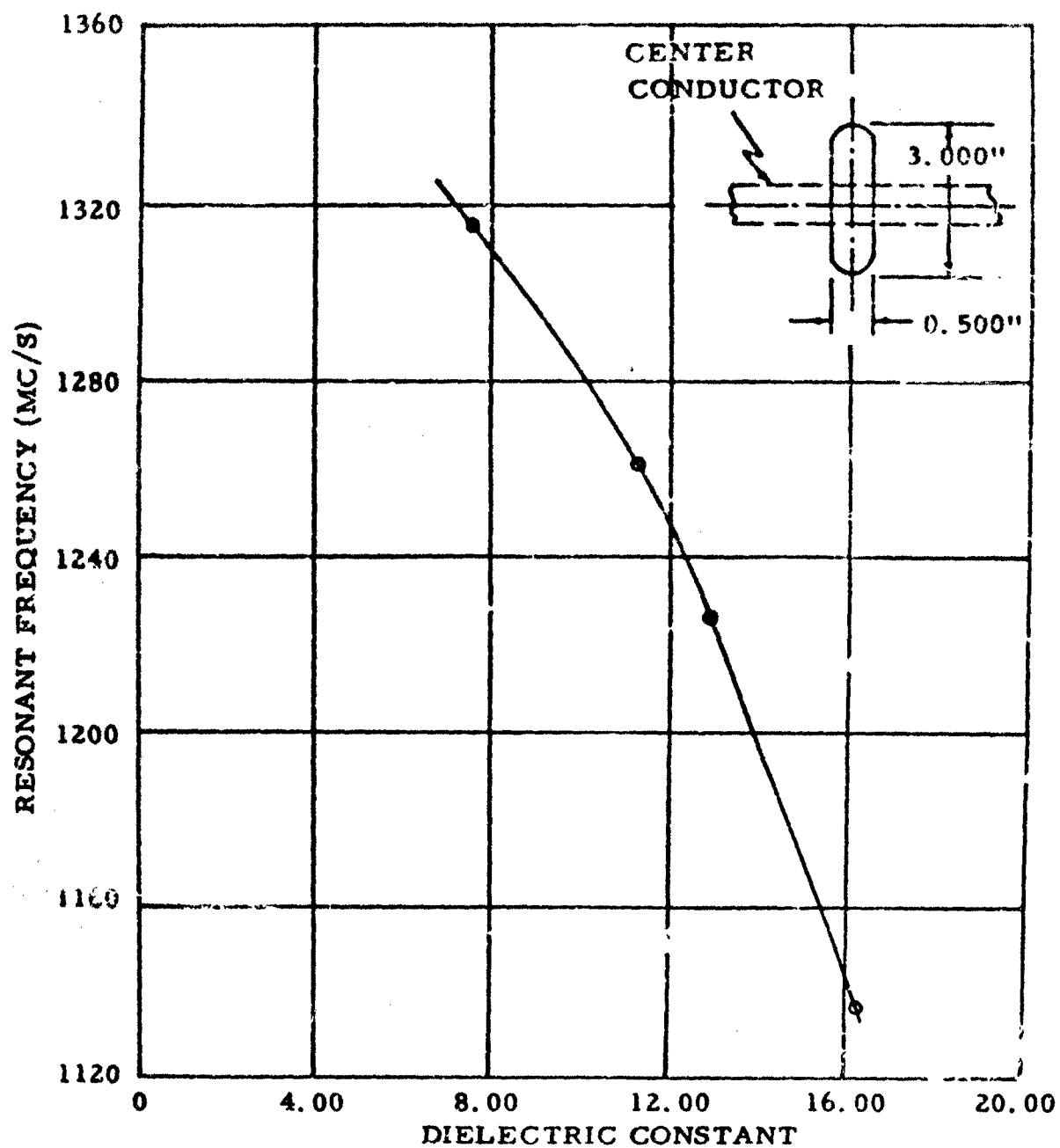


FIGURE 24. RESONANT FREQUENCY AS A FUNCTION OF DIELECTRIC CONSTANT FOR A DIELECTRIC LOADED TRANSVERSE SLOT. (DIELECTRIC MATERIAL FLUSH WITH WALL SURFACES.)

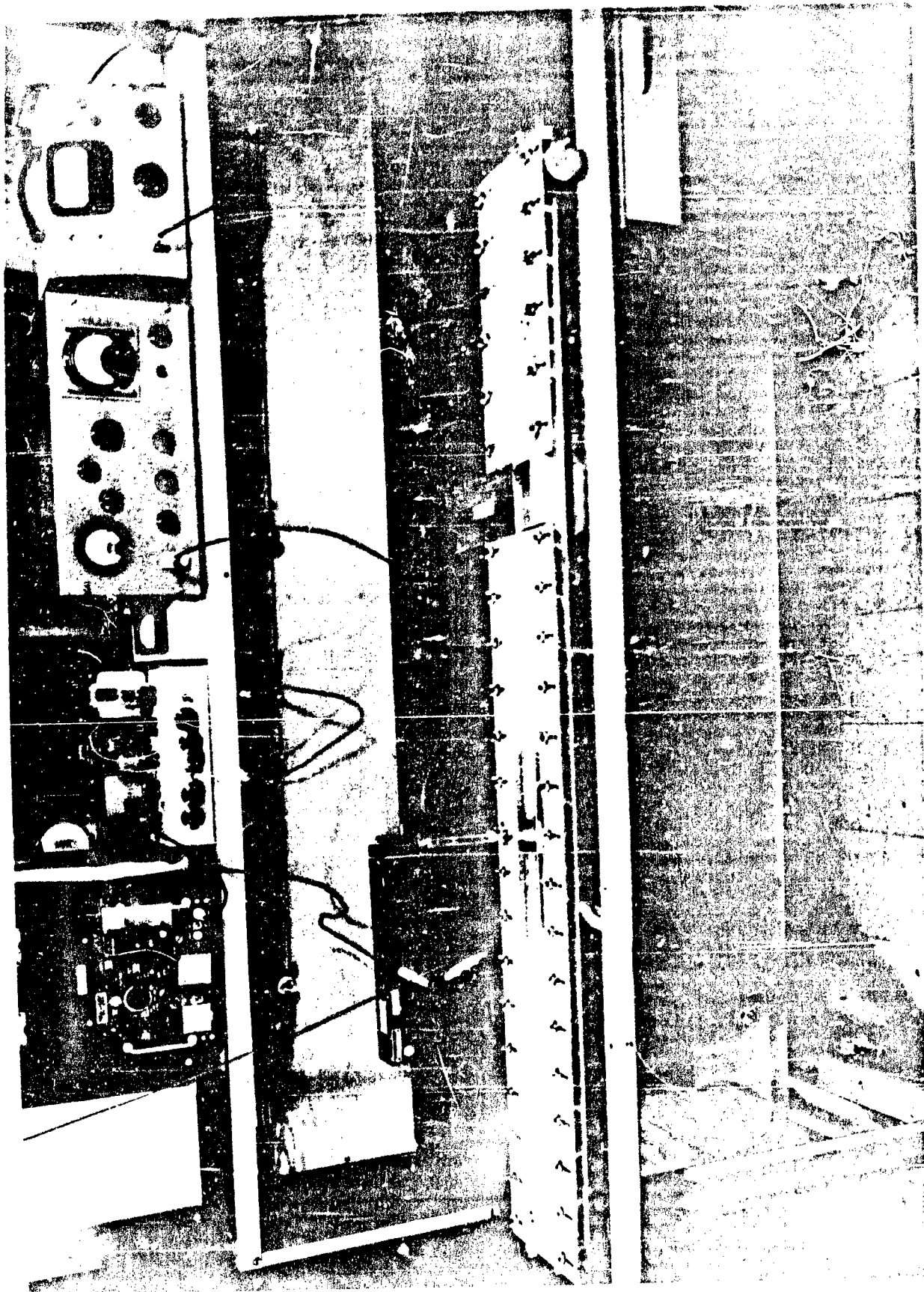


FIGURE 25. 100-OHM TRANSMISSION LINE

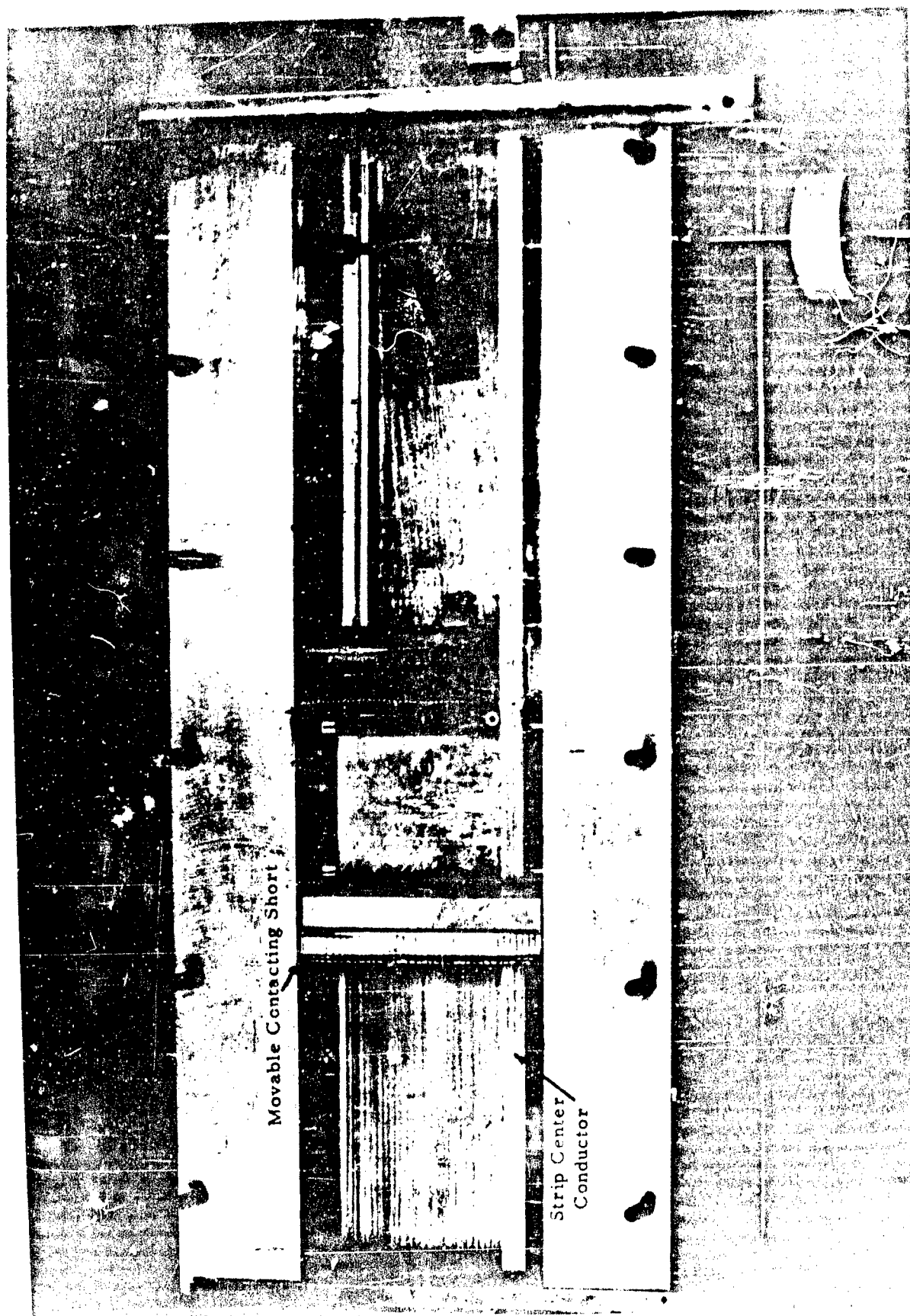


FIGURE 26. 100-OHM TRANSMISSION LINE

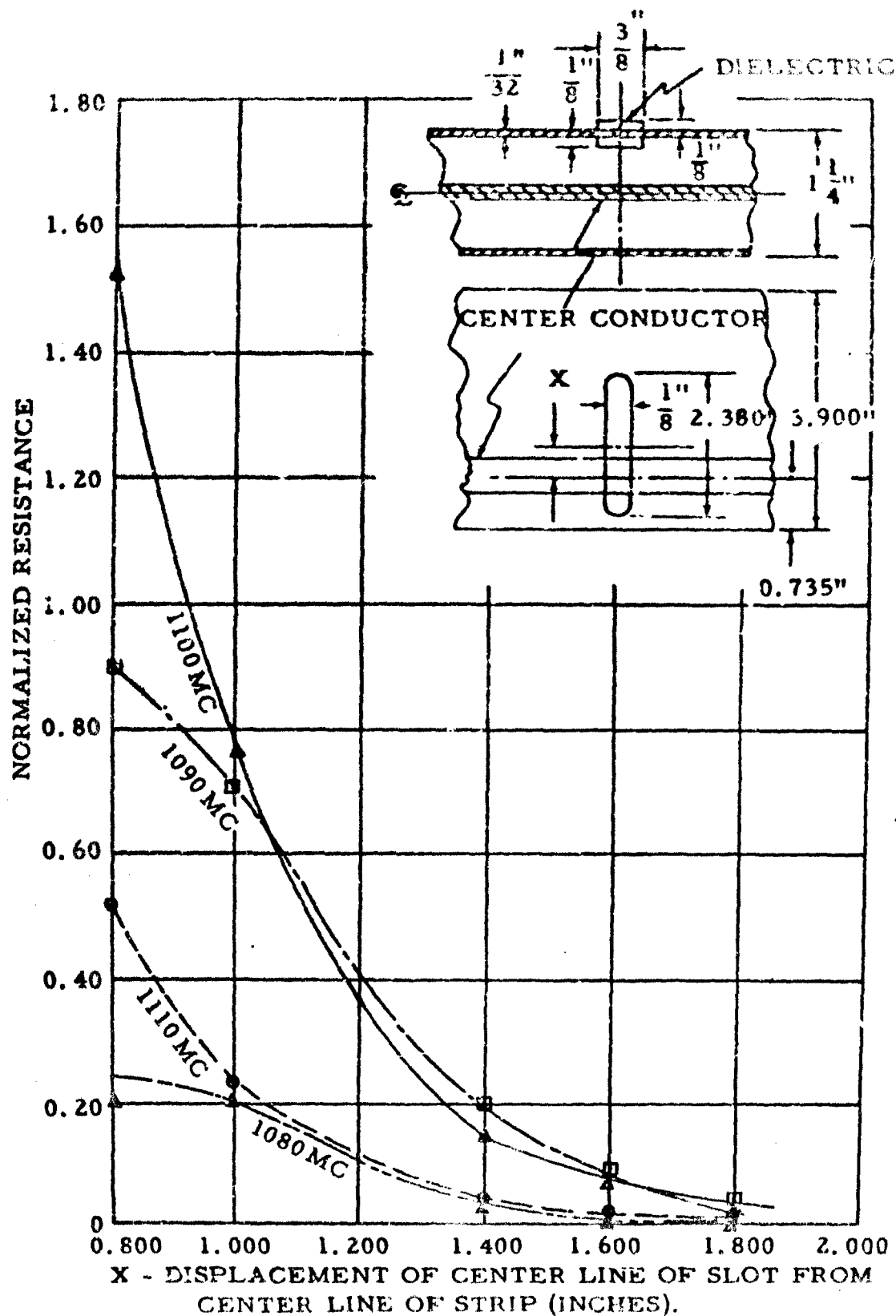


FIGURE 27. NORMALIZED RESISTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY AS MEASURED IN 100-OHM TEM LINE.

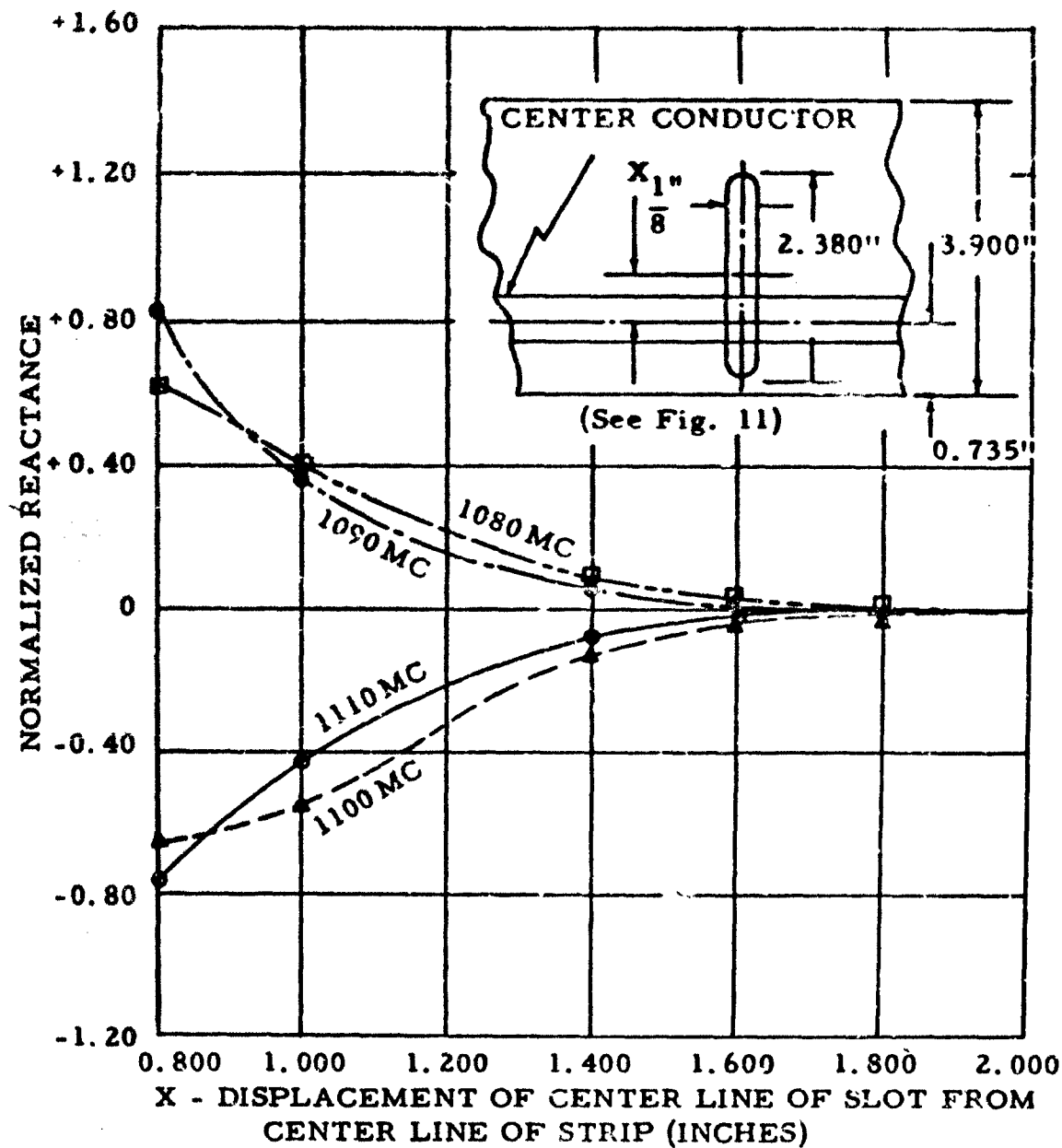


FIGURE 28. NORMALIZED REACTANCE VS SLOT DISPLACEMENT AS A FUNCTION OF FREQUENCY AS MEASURED IN 100-OHM TEM LINE.

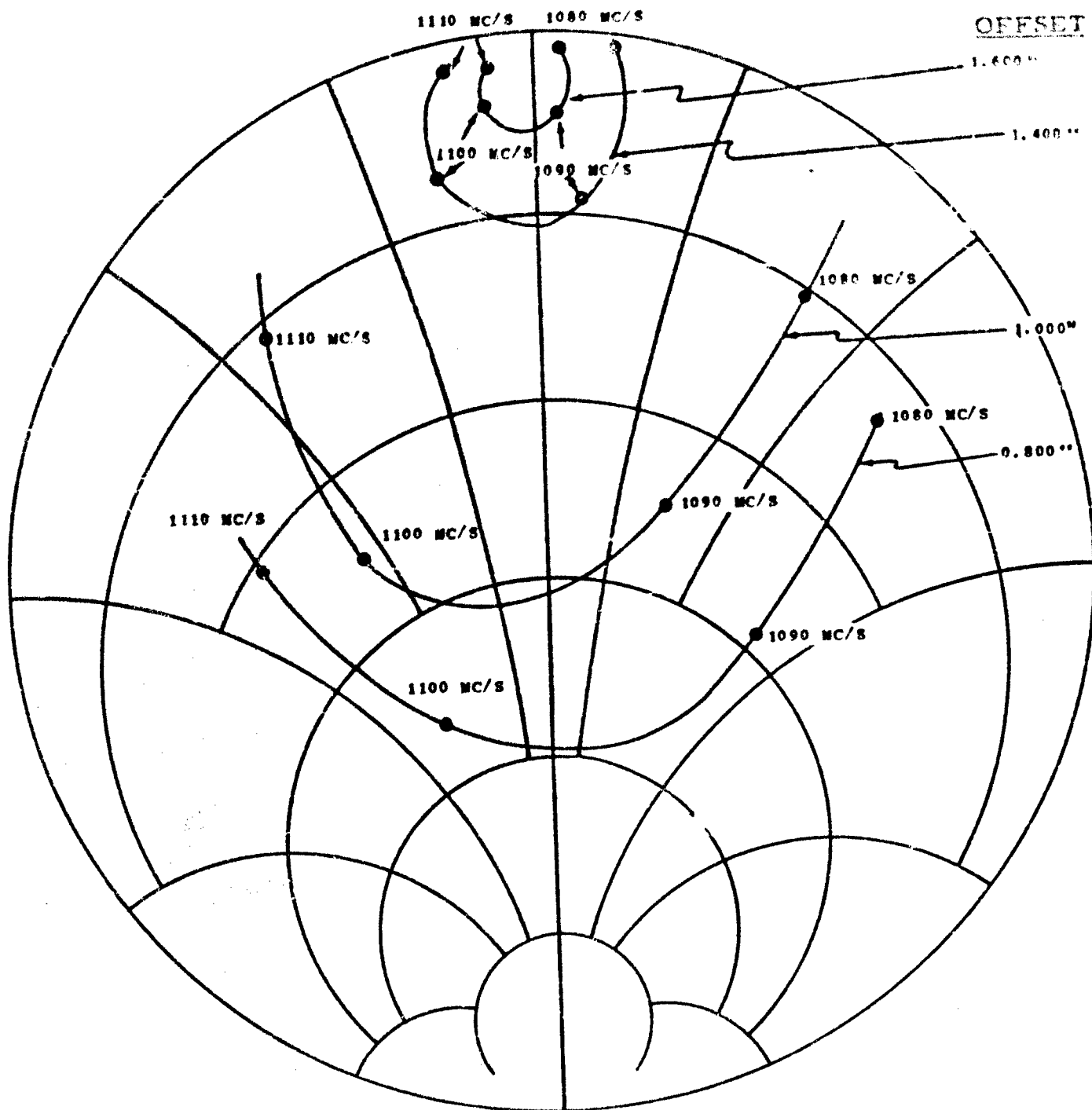


FIGURE 29. IMPEDANCE DIAGRAMS PLOTTED AS A FUNCTION OF OFFSET FOR DIELECTRIC-LOADED TRANSVERSE SLOT. (SLOT AND DIELECTRIC DIMENSIONS ARE THE SAME AS IN FIGURE 11.)

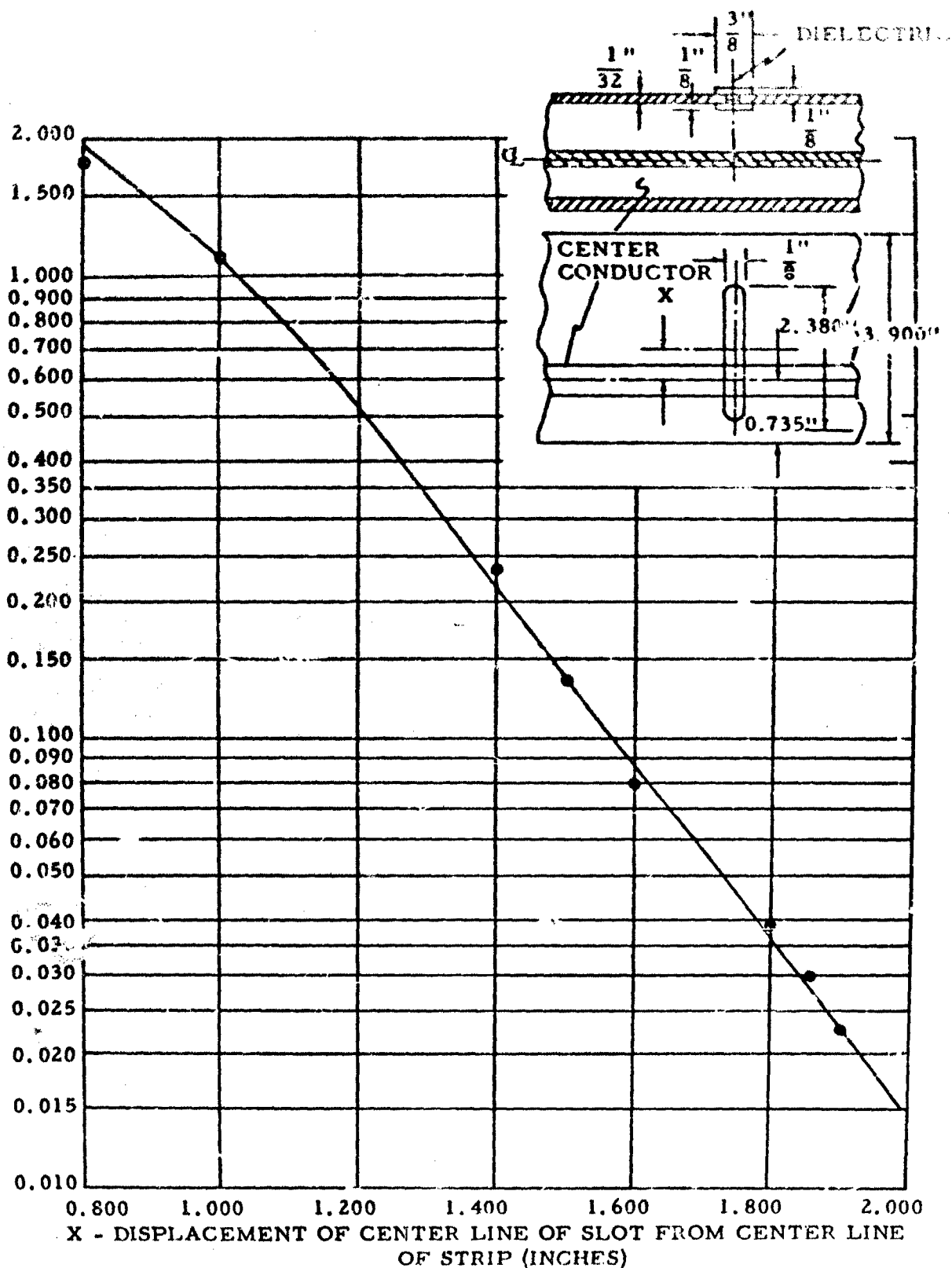


FIGURE 30. RESONANT NORMALIZED RESISTANCE AS A FUNCTION OF OFFSET (FREQUENCY=1095 MC/S) AS MEASURED IN 100-OHM TRANSVERSE SLOT IN 1/32" PLATE. DIELECTRIC MATERIAL ( $\epsilon = 7.5$ ) 5/32" THICK EXTENDING INTO AND ABOVE THE WALL SURFACE.



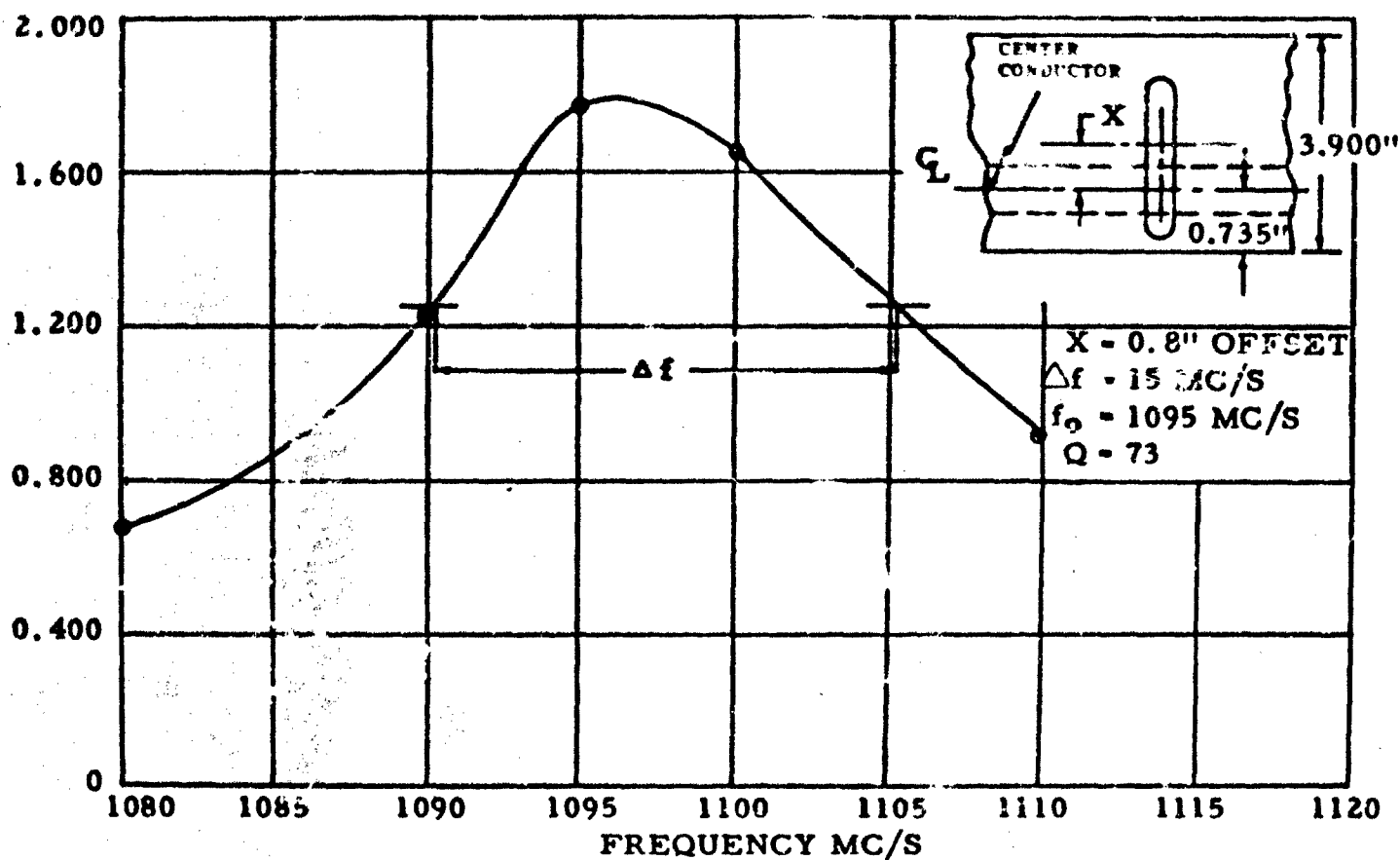


FIGURE 31. NORMALIZED ABSOLUTE IMPEDANCE AS A FUNCTION OF FREQUENCY AS MEASURED IN THE 100-OHM TEM LINE. (SLOT AND DIELECTRIC DIMENSIONS ARE THE SAME AS IN DIAGRAM IN FIGURE 14.)

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Hughes Aircraft Co., Research and Development Labs., Culver City,  
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